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THESIS

DECISION AID FOR PLANNING THE MAINTENANCE OF
ELECTRONIC EQUIPMENT IN THE GERMAN ARMY

by

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March 1992

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In the early stage of the Weapons Acquisition Process (Concept Exploration and Concept Demonstration/Validation Phases) no exact and reliable data are available about expected Mean Times Between Failures (MTBF) and Mean Times to Repair (MTTR) for both the components of a new system or the new system itself. Nevertheless, appropriate decisions have to be made about the number of maintenance facilities at certain military command levels, about the needed quantity of (military and or civilian) maintenance personnel, and about adequate spare stock levels at the appropriate locations.

Wrong planning in this early stage can cause a degradation of the new system's future availability. This is problematic especially with electronic equipment, because maintenance personnel have to be highly specialized, and can not be replaced and retrained as easily as support personnel for trucks or tanks.

A decision aid for the early stages of the acquisition process is needed that offers insight into the behavior of a multi-indenture level electronic system within a three echelon maintenance system, develops alternatives for upcoming decisions, and finally provides information about sensitive factors and their possible tradeoffs, essentially used in budgetary discussions.

The purpose of this thesis is the exact definition of all relevant factors pertaining to the necessary decisions, the review of existing models and tools and their review for applicability. Because the modification of existing programs can not solve the whole scope of the problem due to the use of early generation computer languages, and due to the necessarily new and different approach to the topic, a new simulation program has to be developed. Using object oriented simulation language MODSIM-II, first steps towards this program are made, but remain to be improved and completed in further research work.

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Decision Aid for Planning the
Maintenance of Electronic Equipment
in the German Army

by

Wolfgang Kofer
Captain, Army, Federal Armed Forces Germany
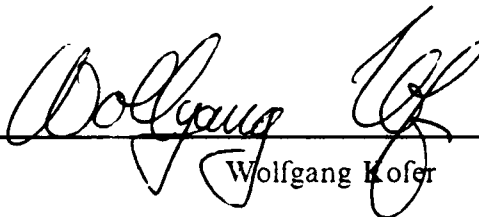M.S.(EE), University of the Federal Armed Forces, Munich, 1978

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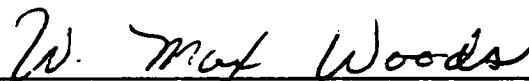MASTER OF SCIENCE IN OPERATIONS RESEARCH

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ABSTRACT

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The purpose of this thesis is the exact definition of all relevant factors pertaining to the necessary decisions, the review of existing models and tools and their review for applicability. Because the modification of existing programs can not solve the whole scope of the problem due to the use of early generation computer languages, and due to the necessarily new and different approach to the topic, a new simulation program has to be developed. Using object oriented simulation language MODSIM-II, first steps towards this program are made, but remain to be improved and completed in further research work.

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THESIS DISCLAIMER

The reader is cautioned that the computer program developed in this research (MODSIM Definition and Implementation Modules) have not been exercised within a complete program. While every effort has been made, within the time available, to ensure that the modules are free of logic errors, they are incomplete and can not be considered validated. Any application of these modules in a MODSIM-program without additional verification is at the risk of the user.

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TABLE OF ABBREVIATIONS AND ACRONYMS

ADM	Acquisition Decision Memorandum
ADT	Administrative Delay Time
AMT	Active Maintenance Time
ART	Active Repair Time
AUTOKO	AUTOmatisiertes KOrps-Stammnetz (automatized corps basic network)
AUTOVON	AUTOmatic VOice Network
BITE	Built-In-Test-Equipment
DES	Direct Exchange Stock
DT	Down Time
EloMat	Electronic Materiel
ILS	Integrated Logistic Support
LDT	Logistics Delay Time
LRU	Line Replaceable Unit
LSA	Logistic Support Analysis
MADT	Mean Administrative Delay Time
MaintEch	Maintenance Echelon
MAMT	Mean Active Maintenance Time
MART	Mean Active Repair Time
MDT	Mean Down Time
MLDT	Mean Logistics Delay Time
MNS	Mission Need Statement
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTTFF	Mean Time To First Failure
MTTR	Mean Time To Repair
NATO	North Atlantic Treaty Organization
RAM	Reliability, Availability, Maintainability

SBS	System Breakdown Structure
TBF	Time Between Failure
TMDE	Test, Measurement and Diagnostic Equipment
TTR	Time To Repair
USALMC	United States Army Logistic Management College

ACKNOWLEDGEMENTS

I. INTRODUCTION AND PROBLEM STATEMENT

A. LOGISTIC SUPPORT IN THE WEAPONS ACQUISITION PROCESS

In the Weapon Acquisition Process, both within the U.S. Armed Forces and within the Federal Armed Forces Germany, the planning for providing sufficient and efficient logistic support for a new weapon system begins in the early stage, in the Concept Exploration Phase and the Concept Demonstration/Validation Phase. Quantity and quality of maintenance personnel, maintenance facilities, spare and exchange parts, storage facilities, tools, manuals and training have to be determined as early as possible, because the lead time from planning to acceptance by budgetary commissions, from contracting parts and tools to actual delivery, and from hiring personnel until their final ability to repair defective equipment is nearly as long as the actual development time of the operational weapon system itself. Using the concept of Integrated Logistic Support (ILS [Ref. 1]), this problem is addressed in the U.S.Army. Nevertheless, it is not uncommon that military equipment is deployed to the active forces without sufficient logistic support. One reason is based on the fact that reliable data for computing necessary and adequate quantities for logistic support facilities are not available at that point of time they are needed.

B. SPECIAL SITUATION WITH ELECTRONIC MATERIEL

Although the personnel training problem with conventional equipment (i.e. equipment based on mechanical, electrical or weapons engineering) can be managed by reassigning existing manpower to a new system after some time for training, this problem is more crucial for electronic materiel. Complex and expensive equipment needs thoroughly trained and highly specified personnel. So it is essential to avoid delays in the planning process, caused by waiting for the availability of data. The approach developed in this thesis concentrates on **electronic equipment**.

C. PRELIMINARY DECISIONS BASED ON EXPERIENCE

For computing the number of maintenance personnel for any new weapon system within a given military maintenance structure, two equipment specific data are essential:

- Mean Time Between Failures (MTBF)
- Mean Time To Repair (MTTR)

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But at that crucial point of time in the Weapons Acquisition Process, at which **numbers** are needed to get started in time, no data are available about MTBF and MTTR for the components of a new system. Even the system itself will not be defined in any precise form. There will be functional units with defined abilities, there will be components with a known technology, there will be first details of a redundancy concept.

But already in the first Acquisition Decision Memorandum (ADM) at the end of the Concept Exploration Phase, **numbers** for quantities are entered. Based on the knowledge of experienced personnel, these numbers are not necessarily wrong. In fact, these initial numbers often turn out to be pretty close to reality. But there is an inherent danger of offering data that can not be justified. In times of economic constraints requests based on intuition generally are not accepted by budgeteers. So the **initial numbers** are adjusted to budget shortages without having any clue about the sometimes fatal consequences for the logistic support system, just because these **initial numbers** can not be backed by any kind of analysis.

D. THESIS OVERVIEW

Operations Research methods seem to be an appropriate way to resolve this situation. Formulating the given problem as a stochastic model and applying adequate estimation and calculation methods should offer **numbers**, which can be analyzed for sensitivity about changes of all kind, and can not be rejected solely due their intuitional origin.

In proceeding towards this goal, the following steps are performed in this thesis:

- In **Chapter II**, the overall problem is described. This includes a presentation of the military environment with emphasis on the support of future electronic weapon systems. Figures 1 and 2 illustrate both the **design structure** of a future electronic system and the **command structure** of its area of deployment, the Federal Armed Forces Germany. Figures 3 and 4 visualize those places in the military environment, where both structures meet - the different kinds of military maintenance facilities. Finally, all facts, rules, subtleties and interactions pertaining to the maintenance problem are described.

- **Chapter III** starts with a review of published analytic models and results related to theoretical maintenance problems. These models are either designed to solve different problems, or they are purely analytic in nature and tend to describe idealized systems. Section C of Chapter III describes the basic flow model that is studied in this thesis, and which is shown in Figure 6.

- Because of the complexity of the interaction between a four-indenture-level weapon system and a three-echelon maintenance system, simulation of stochastic processes is used as the primary modeling tool. **Chapter IV** contains an overview of available simulation models, with emphasis on "TIGER", a FORTRAN-based program used by the Naval Sea Systems Command in the U.S.Navy.

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- Due to the fact that there is no directly applicable simulation model for the given problem, **Chapter V** shows the necessary input modifications in the use of TIGER to obtain useful results for the decisions to be made.

- **Chapter VI** contains the results of the application of TIGER, and describes its major shortcomings when used for the given problem. Basically it can offer only a fixed number of input choices (due to the computer language used), restricting the user to small weapon systems, and it does not enable the modeling of the back-flow of repaired components of repaired systems to their respective stocks.

- It appears that these problems could be overcome by using a modern, object-oriented simulation language like MODSIM-II. **Chapter VII** describes how MODSIM can be used for solving the given problem, and shows compiled code for some of the objects in Appendix C. A full-scale-development of a simulation model for the complex real two-system-interaction world is beyond the scope of this thesis.

- This thesis ends with suggestions in **Chapter VIII** for the necessary future work to be done on this topic, which might help both to increase the efficiency of the logistic part of the Weapon Acquisition Process and to improve the management of the available financial resources within the defense budget of the Federal Republic of Germany.

II. THE MILITARY ENVIRONMENT OF THE UPCOMING DECISION

In this chapter the military environment of the decision model is defined by presenting

- the modular structure of electronic equipment, applied in the weapons acquisition process of the Federal Armed Forces Germany

- the general maintenance concept to provide support to these electronic systems in the German Army[Ref. 2]

- the command structure of the German Army with combat, combat support, communication and logistic forces.

A. MODULAR STRUCTURE OF ELECTRONIC EQUIPMENT

Electronic weapon systems in the notation of the German Army[1] include weapon systems with essential electronic components (e.g. battle tanks with an electronic weapon guidance system, Artillery weapons controlled by a data link system), command- and control systems, signal- and communication systems (e.g. AUTOVON (US) / AUTOKO (GE)), reconnaissance systems (e.g. Artillery reconnaissance radar) and signal- and communication- intelligence systems. All these electronic weapon systems are generally structured in 5 indenture levels[2] as seen in Figure 1 on page 5:

1. The **complete system** itself - as an illustrative example we will look at a *Battle Tank* assumed to be developed.

2. **Subsystems** or **A-Units** are functional units or self contained units within a weapon system. In our example the (non-electronic) *Gun,* the (electronic) *Weapon Guidance Subsystem,* the (electronic) *Command- and Control Subsystem* and the ("semi"-electronic) *Power Supply Subsystem* are A-Units.

3. **Assemblies** or **B-Units** are integral parts of A-Units. *Target Data Storage* and *Data Display Terminal* are B-Units of the *Command- and Control Subsystem.*

4. **Subassemblies** or **C-Units** and

5. **Elements** or **D-Units** are both the smallest replaceable components of a weapon system. The "black box" *Updated Target Data Memory* is a C-Unit (subassembly) that will not be repaired in the field, the *Microchip A4512* is a D-Unit (element) that can not be repaired at all.

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1 This structure is slightly different from that used by the US Army in the **Logistic Support Analysis (LSA)** procedures [Ref. 1, p.2-17].

2 The term **indenture level** is also used by the US Army to address the different levels of a "hardware generation breakdown" [Ref. 1, p. 2]
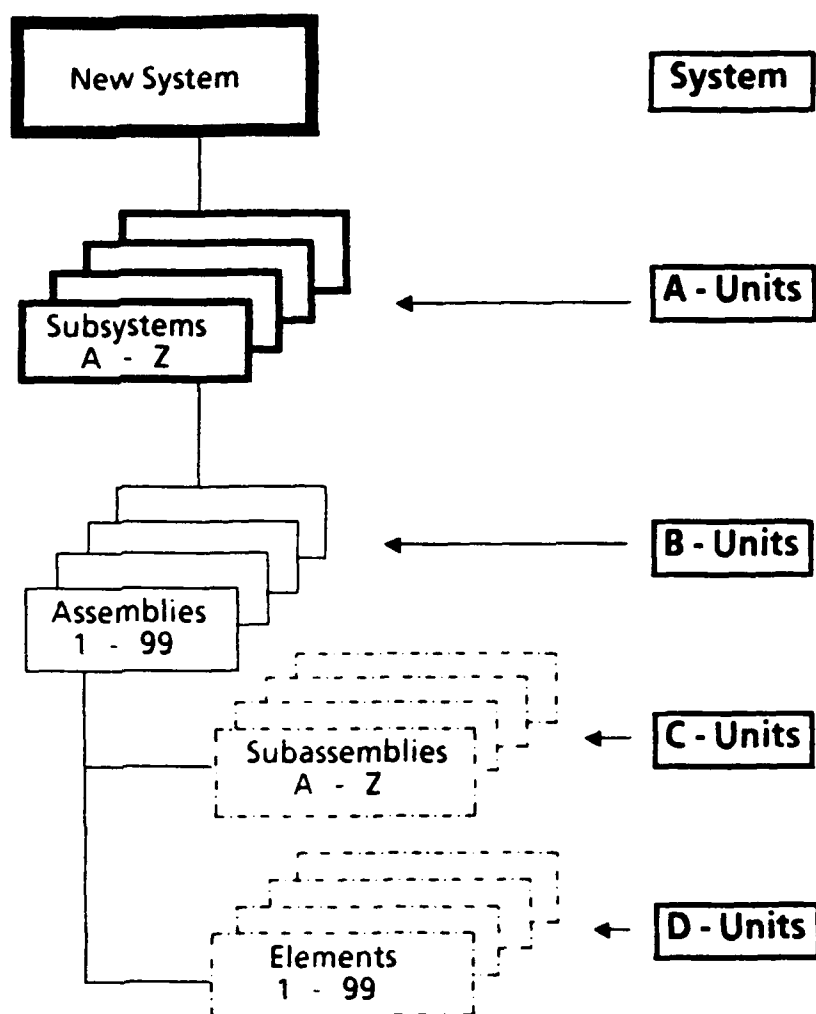
Figure 1.   Modular Structure of Electronic Equipment in the German Army

B.   MAINTENANCE CONCEPT FOR ELECTRONIC EQUIPMENT

In general, the maintenance of any electronic weapon system is performed both by military personnel for conventional technology (engine, steering system etc.) and by military personnel for electronic technology. In this paper we concentrate only on the maintenance concept for electronic equipment, shown in Table 1 on page 6 [Ref. 2].

Table 1. MAINTENANCE CONCEPT FOR ELECTRONIC MATERIEL

Level of System Structure	Test Procedure	Maintenance Procedure
System	User (Notation in the German Army: Maintenance Echelon 1)	
	Built-In-Test-Equipment (BITE) Technical Manuals	Report of defective **A-Unit** to Organizational Maintenance
A-Units		On-System modular maintenance by replacement of **Line Replaceable Units (LRU)**: **B-Units**; **C-Units** and **D-Units** if appropriate
	Organizational Maintenance (Maintenance Echelon 2)	
B-Units	LRU-Test by **Test, Measurement and Diagnostic Equipment (TMDE)** / Technical Manuals	Off-System modular maintenance of defective **LRU** by replacement of **C-Units** and **D-Units**
	Intermediate Maintenance (Maintenance Echelon 3)	
C-Units	Technical Manuals, Contractor manuals, special equipment	Repair of **C-Units** by replacement of **D-Units**
	Depot Maintenance (Maintenance Echelon 4) or commercial maintenance (Maintenance Echelon 4)	
D-Units	no test - no repair - recycle or discharge	

C. MILITARY COMMAND STRUCTURE OF THE GERMAN ARMY

Germany is undergoing extensive political, economical and social changes since the unification on October 3rd 1990. As a consequence, the military structure of the Federal Armed Forces is subject to changes in the years ahead. The structure presented in the next paragraphs is the general structure of the Army, which will persist whatever changes and reductions might occur. Specific details and exact quantities are omitted since they are irrelevant for the stated decision problem.

1. Combat, Combat Support and Communication Forces

The highest command level below the Federal Ministry of Defense, Headquarter of the Army, at BONN is an Army Corps. The general command structure of an Army Corps[3] is shown in Figure 2 on page 7.

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3 There are 3 Army Corps in the German Army
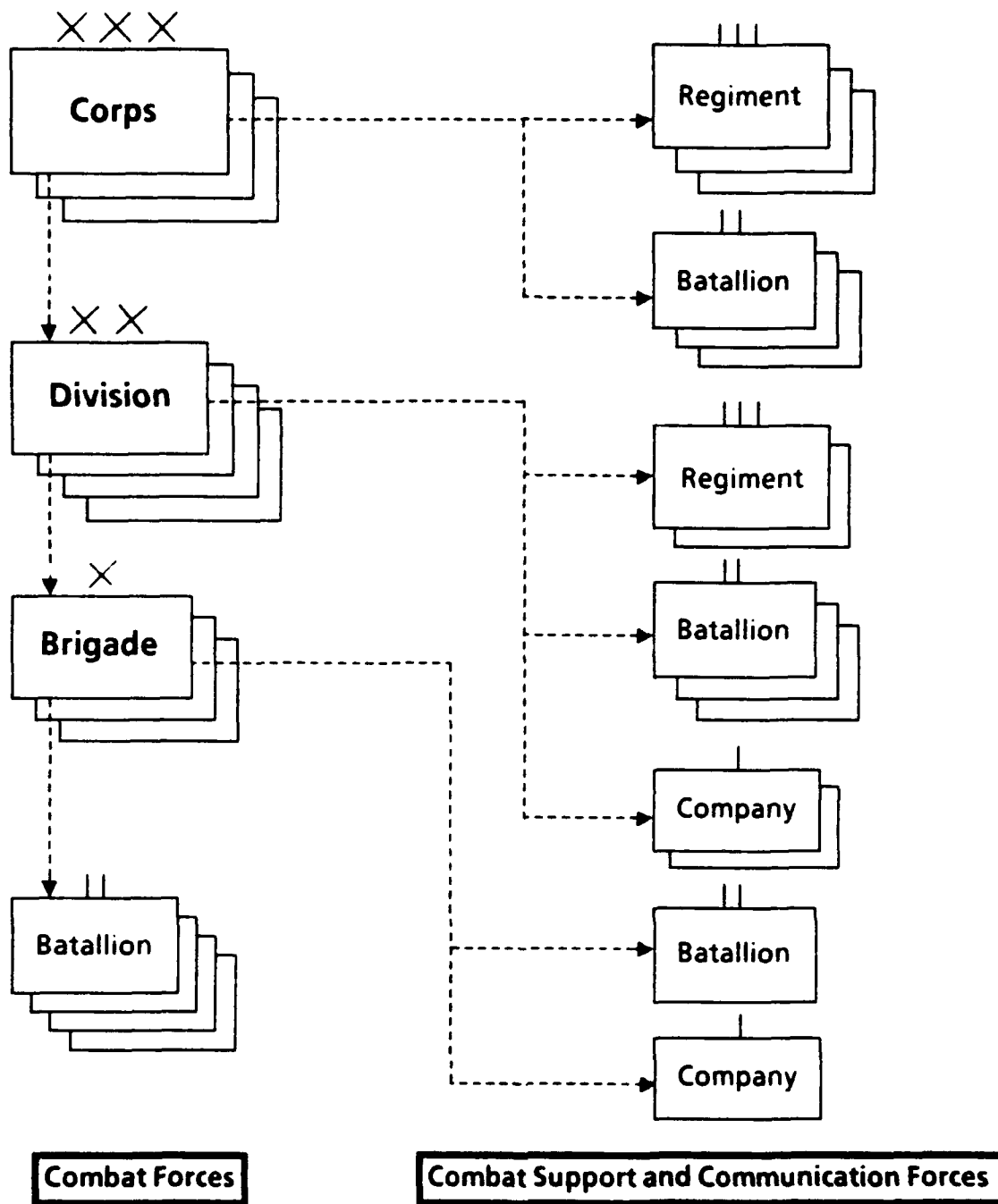
Figure 2.   Command Structure of a German Army Corps

While an electronic weapon system used in the Combat Forces is mostly deployed in large numbers (e.g. there will be some thousand battle tanks with electronic subsystems), the many different electronic weapon systems deployed in the combat support and communication forces often consist of only a small number of units (e.g. there will be only some 15 units of a communications- and signal-intelligence-system within the entire Army).

2. Logistic Forces (Maintenance Component)

The structure of the maintenance component is presented completely, but the supply component is shown only as far as it is under operational control of the maintenance component.

a. Organizational Maintenance

Organizational Maintenance (Maintenance Echelon 2), both for conventional materiel and for electronic materiel (EloMat), is provided by a Maintenance Platoon for every Batallion, and by a Maintenance Group for every Company that is not under operational control of a Batallion (See Figure 3).

I I	Batallion
I	Company
●●●	Platoon
●●	Group

⊃—⊂ Tactical Sign for Maintenance facilities
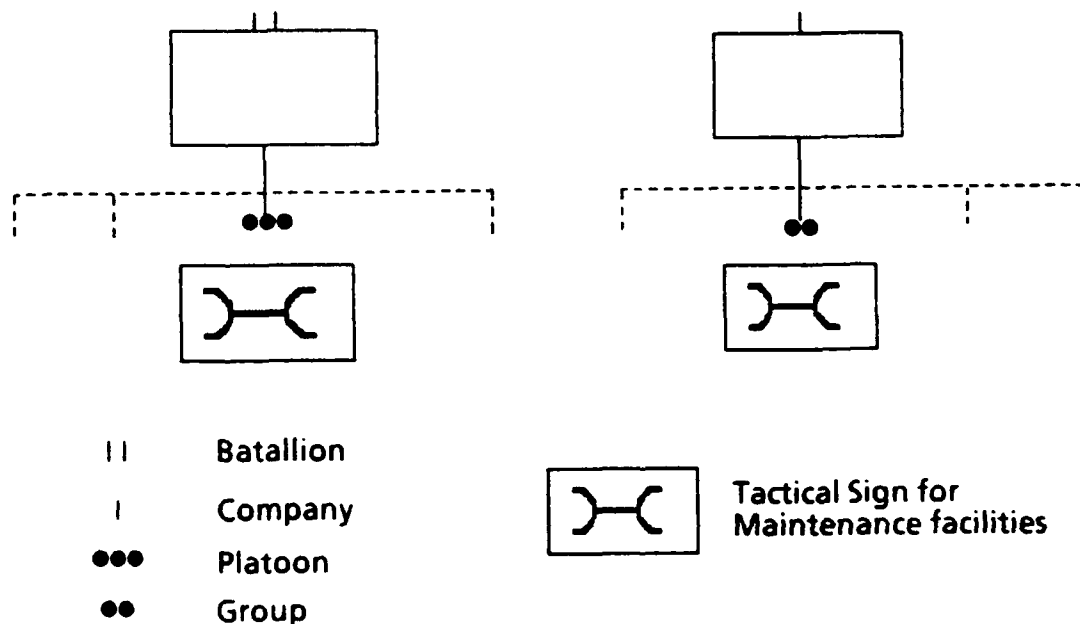
Figure 3.   Structure of the Organizational Maintenance

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The quantity of the maintenance personnel is determined by the needed capacity, but at least 1 soldier has to be available at each Batallion Company for each type of weapon system. There is no supportive exchange of maintenance personnel between Batallions Companies. The skill-level has "only" to be appropriate for localizing defective LRU[4] by using BITE or straightforward traditional techniques, and for replacing them. Jobs requiring higher qualifications might be completed, if the personnel can perform them with the available tools and within the capacity limits of the unit.

b. *Intermediate Maintenance*

The structure of the Maintenance Troops [5] (Maintenance Echelon 3) is shown in Figure 4 on page 10.

Each **Army Corps** has 2 active Maintenance Batallions, servicing both the conventional materiel and the electronic materiel (EloMat) of the Corps' Combat Support Forces and Communication Forces. Each **Division** has 1 Maintenance Batallion; 2 Companies service the conventional materiel of the Division's Combat Support Forces and Communication Forces; 1 Company for electronic materiel services both the Division's troops and the electronic materiel of the Brigades - though every **Brigade** has its own Maintenance Company, there is no service for electronic materiel on the Brigade's command level.

The quantity of the maintenance personnel is determined by the needed capacity and the number of different fields of technology applied in the new system ("pure" electronic, optronic, Laser, Radar etc.). Many jobs are performed by mobile maintenance teams, and at least 2 soldiers have to be available at each Maintenance Batallion Company (EloMat) for each type of supported electronic weapon system and/or each technology used. There is no supportive exchange of maintenance personnel between Corps and/or Divisions. Though localization of defective C- and D-Units for certain systems is performed by different personnel applying the complex Test, Measurement and Diagnostic Equipment (TMDE), the skill-level generally has to be appropriate for localizing defective C- and D-Units using traditional techniques, and for replacing these units. Again, jobs requiring higher qualifications might be completed, if the personnel can perform them with the available tools and within the capacity limits of the unit.

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4 See pages xi and xii for a List of Abbreviations and Acronyms

5 based on the actual structure of the Army in the 10 Western States of Germany (the former West Germany)
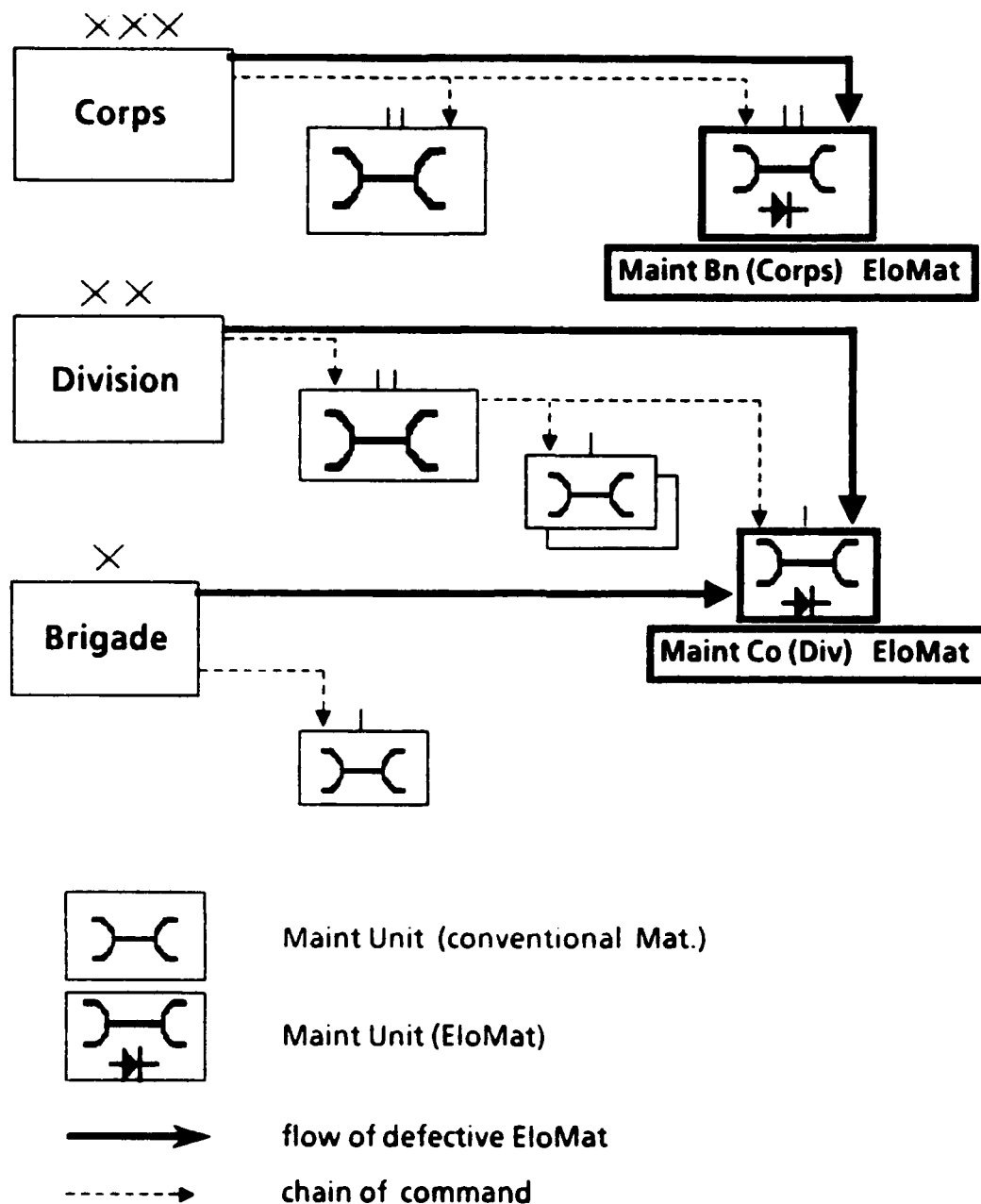
Figure 4. Structure of the Maintenance Troops

c. Depot Maintenance

Materiel with damages requiring work in Maintenance Echelon 4 leaves the combat zone and is transported to central repair shops at Army Maintenance Installations, at depots or at commercial facilities.

d. *Interactions*

While personnel of the Organizational Maintenance might perform jobs of a higher Maintenance Echelon if capacity constraints, skill levels and available tools allow, maintenance teams of the Maintenance Troops can be ordered by their operational command to work on surplus jobs on Maintenance Echelon 2, if this is the only way to increase the availability of a certain electronic system at a certain military unit. However, this regulation will not be regarded in this model, because it should be constrained to emergency situations.

e. *Replacement Parts Supply and Storage*

All considerations about replacement of LRU (B-Units/Assemblies) at Maintenance Echelon 2 and C- (Subassemblies) and D-Units (Elements) at Maintenance Echelon 3 are based on the immediate availability of replacement parts at these maintenance facilities. Supply of these parts only on demand would take far too long to guarantee shortest possible times to repair.

To decrease the down time of a weapon system, each Maintenance Batallion (intermediate maintenance level) has a Direct Exchange Stock (DES) for B-Units, and if appropriate, also for selected C- and D-Units (see Table 1 on page 6). The military user delivering a defective B-Unit immediately receives, if available, an intact B-Unit in exchange, while the defective B-Unit will be added to the DES after repair. So the downtime for a B-Unit (consequently the downtime of the failed system after being diagnosed and before actually being repaired) is reduced to the amount of transportation time between military user and its assigned Maintenance Batallion. Of course, the Maintenance Batallions also have a stock for the C- and D-Units needed for repair of the defective B-Units.

Consequently, the model has to consider the necessary stock levels at the facilities of Maintenance Echelon 2 and 3, but not further back in the line of supply which will be assumed to have unlimited capacity.

D. CONSEQUENCES FOR THE UPCOMING DECISION

Resulting from the facts presented above, certain range limitations for the following decision areas have to be observed:

1. Organizational Maintenance

Due to the concept of Organizational Maintenance, each Batallion/Company supplied with a certain electronic weapon system has to be able to perform repair jobs on its own equipment at Maintenance Echelon 2. So the decision to be made is not

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about the fact of creating an installation at all, but "only" about the number of repair personnel, which will be at least 1.

To keep the Organizational Maintenance as highly mobile as the weapon system itself, a spare stock of A-Units generally will not be kept at the organizational level. However, establishing such a (limited) spare stock might be one way to increase the system availability, and can be one feature of the upcoming decision.

2. Intermediate Maintenance

Because some electronic weapon systems, especially those deployed in very small numbers, are designed to avoid any work at Maintenance Echelon 3, the number of repair personnel for a certain weapon system at Maintenance Echelon 3 might be 0. If Maintenance Echelon 3 is appropriate, there are several choices for the location of maintenance facilities. In Table 2 the possible **mutual exclusive** alternatives are shown. In these cases stock levels for both the DES (Direct Exchange Stock) and the C- and D-Units stock have to be determined.

Table 2. MAINTENANCE FACILITIES AT MAINTENANCE ECHELON 3

Command level of system deployment	Number of maintenance facilities	Sum for entire Army
Brigade	1 per Division	12
Brigade + Division	1 per Division	12
Division	1 per Division	12
Division + Corps	1 per Corps	3
	1 per Division and per Corps	15
Corps	1 per Corps	3
Brigade + Division + Corps	1 per Corps	3
	1 per Division and per Corps	15

3. Depot Maintenance

The decision about the quantity of the maintenance personnel at the depot level is not as important as at the organizational and intermediate level at this stage of the decision problem. Therefore this problem will not be addressed, nor that of spare stock levels at Depot Maintenance facilities which will be assumed to be infinite.

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III. THE THEORETICAL BASIS FOR THE UPCOMING DECISION

A. GENERAL APPROACHES FOR MAINTENANCE CONCEPTS

A survey of the articles published in the respective journals within the last years shows numerous studies and papers about the modeling of optimal maintenance policies for single- and multi-unit electronic and non-electronic systems; for example see [Ref. 3, 4, 5, 6 and 7]. An overview especially about models for multi-unit systems is given in [Ref. 8].

These "... Multi-unit maintenance models are concerned with optimal maintenance policies for a system consisting of several units of machines or many pieces of equipment, which may or may not depend on each other ... The objective is to find optimal repair rates (i.e., number of repairmen, number of repair facilities, etc.) ..."[Ref. 8].

Many of these models consider specialties needed in the defined military environment like

- more than one repair facility in the system

- failed equipment has to be sent to a certain repair facility

- multi-echelon maintenance structures.

So, the reader might ask, are we to invent the wheel again ? There are three main reasons for a different approach to solve the given real-world problem.

1. Distributions for Failure and Repair Times

In many models mathematical procedures are simplified by assuming an exponential distribution for both the times between failures and the repair times. Especially regarding electronic components having a high reliability, this assumption may be unrealistic for the times between failures. We will observe a high mean time between failure (MTBF) with very few failure times being close to zero. Jardine and Buzacott [Ref. 6, p.286] even state that it is realistic to assume that there are no failures at all between the start-up of the observed equipment ($y = 0$) and some time $y > 0$.

The assumption of exponential distribution may or may not be realistic for the repair times. The exponential distribution for repair times says that the probability for completion of a repair job in the next k units of time does not depend on how long the repair job has been worked on already - not too realistic for some types of repair! There will be a minimum time for each repair job (receiving the job, preparing the work place,

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performing test and measurement procedures, performing the genuine repair etc.). Though there will be no values close to zero, we will observe a highly skewed distribution with a lot of small TTR-values (caused by easy detectable mechanical or thermal damages followed by simple replacement of the damaged component) and, nevertheless, a non-negligible number of observations with distinctive higher values (caused by short-circuits etc.). Though some studies (e.g. see in [Ref. 8 ,p.5]) use general repair times, the assumption of exponentially distributed TTR seems reasonable, when the nature of the repair is random due to the random type of failure.

2. Optimality Criteria

Another great drawback is the use of all kinds of costs as optimality criteria to achieve an optimized maintenance concept. This is legitimate and appropriate in all described problems, especially in cases regarding not only costs for repair personnel and repair facilities, but also costs for spare part inventories and costs in form of lost revenues due to downtimes caused by failures. While lost revenue is irrelevant in the military environment (though a lost battle has an enormous economic impact), most other types of costs are not applicable in the described real-world situation, because they are neither known nor can be acquired in this early stage of the acquisition process.

Other models additionally or exclusively use the availability of the system as a decision criterion - for example see [Ref. 7, p. 551]. This approach is promising pertaining to the given problem.

3. Available Information

Due to the fact that the future system is not defined exactly at this point of time, we have to make a **decision under extreme uncertainty** . Because we do not have any test results for single Subsystems, Assemblies or Subassemblies (with the exception of standardized equipment), we have to create, in the most controlled way possible, "probable probability distributions" for the times between failures for each proposed and yet to be developed component of the planned System Breakdown Structure (SBS). Based on this "solid ground", we have to come to a recommendation for the future maintenance concept for this new electronic equipment.

Cho and Parlar [Ref. 8, p.3] realize that dilemma by stating "... Very few papers have been written on the area of maintenance models with incomplete information ...". The need for further research on this field within the military environment is emphasized in a 1984 Notice of the Secretary of the Navy, D.E. Mann [Ref. 9, p.87]: "Although there is considerable uncertainty early in the acquisition process, every effort must be made to use the best available data and techniques in developing estimates."

B. IDEALIZED APPROACH FOR GIVEN PROBLEM

1. Distributions for Time Between Failure

Regarding possible failure scenarios and evaluating the actual literature (e.g. see [Ref. 6]), the Weibull and the Gamma distribution are the most appropriate to use for time between failure.

The Weibull density function has the following form [Ref. 6, 10 and 11], also used by the statistical package GRAFSTAT [Ref. 12]:

$$f_W(t) = \frac{c}{\alpha} \left(\frac{t}{\alpha} \right)^{c-1} e^{-\left(\frac{t}{\alpha} \right)^c} \; ; \; 0 \leq t < \infty, c > 0, \alpha > 0$$

and its cumulative distribution function has the form:

$$F_W(t) = 1 - e^{-\left(\frac{t}{\alpha} \right)^c}$$

The Gamma density function has the following form [Ref. 13, p. 165, and 12]:

$$f_G(t) = \frac{t^{\alpha-1}}{\beta^\alpha \, \Gamma(\alpha)} \; e^{-\frac{t}{\beta}} \; ; \; 0 \leq t < \infty, \beta > 0, \alpha > 0$$

Its cumulative distribution function can not be obtained in closed form.

Using appropriate **shape**-parameters ("c" for the Weibull, "β" for the Gamma) and **scale**-parameters (α), both distributions are highly flexible to fit Exponential and Normal distributions, and any other distribution being "humped in the middle". This "flexibility" is shown in Figure 5 on page 16.

Jardine and Buzacott [Ref. 6] use the 3-parameter Weibull density function with the third parameter "γ", the **location parameter**. This is not appropriate in our situation. Though the number of failures of one component occurring within a short time will be very small, this possibility has to be regarded because there might be imperfect repairs. Pertaining to this fact many studies assume that repaired components are as good as new (e.g. in [Ref. 7]), which will not be realistic in a military environment - neither in war nor in peacetime. Consequences of imperfect repair on system reliability are shown in [Ref. 14].

So the approach to the given real-world problem described here will use either the 2-parameter Weibull or the Gamma distribution to model the time between failures and the exponential distribution to model the repair times.

15
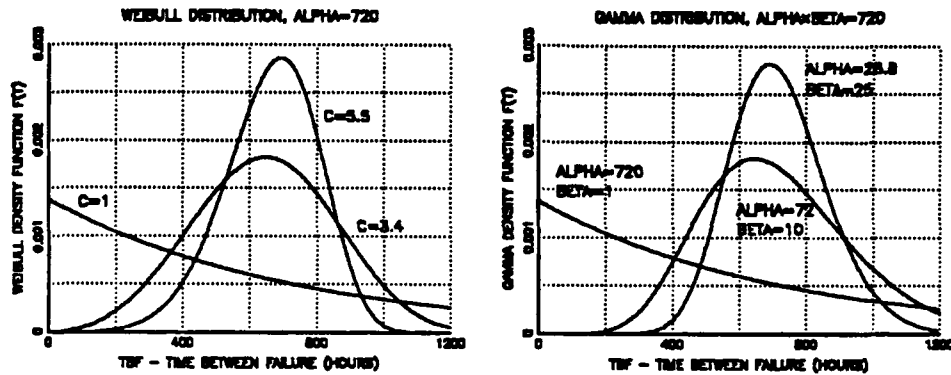
Figure 5.   The Flexibility of the Weibull and Gamma Density Functions

2.   Links between Failure and Repair Times

Many authors assume exponentially distributed repair times, but most of them also assume the same repair time distribution for all components which are subject to failure. This is partially unrealistic for the described problem. There is not only a difference in repair times between changing a defective Subsystem in Organizational Maintenance (which can be assumed to be relatively constant due to "design to quick replacement"), and finding the defective Subassembly or Element within an Assembly when repairing it in Intermediate Maintenance (which could be covered by assumption of maintenance echelon specific repair times - a concept used by Madu in [Ref. 3, p. 959 - 960]), but there are also decisive differences in repair times between different technologies at Intermediate Maintenance. Each specified component "X" of the future system will be characterized by 3 parameters:

1. c_X-value for the "probable" distribution for times between failures for component "X" (in case of the Gamma distribution the β_X-value)

2. α_X-value for the "probable" distribution for times between failures for component "X"

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3. $MTTR_x$, the "probable" technology dependent MTTR for component "X"

Pertaining to this necessary approach no literature at all was to be found.

3. Source of Information

With the future system just being defined in terms of a SBS (system breakdown structure), there are no data available for the necessary values of c_x or β_x, α_x and $MTTR_x$. Jardine [Ref. 6, p.288] mentions three basic approaches to estimate these data. While the third approach - models based on physical, chemical or other mechanisms of failure - is not appropriate due to the uncertainty of the engineering design at the relevant point in time, a combination of the other two approaches seems applicable:

1. Analysis of empirical data on a similar design

2. Prediction of system reliability from component reliability

With each single repair job done at Maintenance Echelon 2, 3 or 4 within the German Army, a lot of data are gathered offering information about the proceeding of the job over time. Active maintenance times (AMT = TTR = ART (Active Repair Time)) and the MTTR can be obtained directly. Administrative delay times (ADT), caused by maintenance system inherent procedures and geographical distances, and logistic delay times (LDT), caused by ordering and waiting for spare parts not in stock at the maintenance facility can be estimated. Throughout the lifetime of each single weapon system, data are gathered about down times from which the times between failures (TBF) can be obtained. From these known TBF data the appropriate α, β and c-values can be obtained by using GRAFSTAT [Ref. 12, "FITTING PROBABILITY DISTRIBUTIONS"].

Though we do not know the exact characteristics of the components of the future weapon system, we can assume that these values are not too different for components with similar functional characteristics (e.g. antennas, terminal keyboards, displays, RADAR-emitters, military computers etc.) and within the same level of technology, which have already provided plenty of realistic data from the actual use in the real (peacetime) world. Definite sources of trouble will be a differentiation of similar components originating from different contractors, the evaluation of offered "next technology generation" components and the adaptation of the data to a wartime scenario (further research has to be done on these features).

If a totally new functional configuration will be introduced, the subcomponents still will offer a chance to find appropriate values, from which the reliability for the next higher SBS-level can be computed.

4. Optimality Criterion

As pointed out in III.A.2., system availability is one meaningful optimality criterion for evaluating future maintenance performance problems. This availability definitely depends upon the reliability of the system, but can be increased decisively by an appropriate maintenance system. Before proceeding further, we need to recall the definitions and characteristics of **reliability** and **availability**.

- Reliability

The probability that a weapon system will perform its intended function for a specified period of time under stated conditions [Ref.6, p.285, 15, p.32, and 16, p.20].

The reliability function R(t) is well defined as

$$\int_t^\infty f(t)dt$$

where $f(t)$ is the probability density function of the time between failures. Therefore the reliability function $R_w(t)$ for the general form of the Weibull distribution has the form $(c > 0, \alpha > 0)$:

$$R(t) = \int_t^\infty \frac{c}{\alpha} \left(\frac{t}{\alpha}\right)^{c-1} e^{-\left(\frac{t}{\alpha}\right)^c} dt = e^{-\left(\frac{t}{\alpha}\right)^c}.$$

Although there is no closed form for the reliability function for the Gamma distribution, we could use the incomplete Poisson Sum for integer values of α to compute R(t).

The reliability values obtained by this approach depend on 2 features:

- the distribution of the times **between** failures, which is **independent from the applied maintenance concept**

- the length of the specified period of time, which can be "varied to achieve any reliability value desired" $(R \to 0$ for $t \to \infty$, $R \to 1$ for $t \to 0)$

Due to the independence from the maintenance concept, and due to possible bias by "conveniently" choosing the length of the time period, reliability is not suitable as an optimality criterion in the given problem.

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- Availability

The probability that a weapon system is in the operable state at any point of time when used under stated conditions[Ref. 15 , p.29 and 17, p.19].

A generally used computational formulation of availability is the operational availability being defined [Ref. 17] as

$$A_O = \frac{MTBM}{MTBM + MDT}$$

where MTBM is the Mean Time Between Maintenance and MDT is the Mean Down Time. MDT itself is the sum of MAMT (Mean Active Maintenance Time), LDT (Logistics Delay Time) and ADT (Administrative Delay Time). Considering a long period of time this approach offers an average availability, which strongly depends - via MDT - on the applied system specific maintenance concept. However, MDT itself can not be handled as an average value, because this approach would not take into account worst case scenarios, where many components might fail within a short period of time, imposing decisively more workload onto the maintenance system in some periods of time than under the mean value approach.

This average availability is the appropriate optimality criterion for the given problem. Note that there is a decisive difference between the availability (combat readiness) of a military unit, and the availability of a single unit of a weapon system within this military unit. Only the latter will be covered here.

C. THE STOCHASTIC MODEL OF THE MAINTENANCE SYSTEM

The system specific maintenance system, determined by the number of deployed systems and introduced in I.B.,C. and D., can be described as a stochastic network, shown in Figure 6 on page 20 (See in comparison also [Ref. 18, p. 18]).

1. Fixed Parameters

Its characterizing fixed parameters are defined in Table 3 on page 21. All given times are in hours, based on a (peacetime) average of 7 hours of use per day, 5 days of use per week and 48 of these weeks per year. E.g., $ADT_3 = 35$ means a delay of 35 hours of simulation time, which is about a week in peacetime, but 1 day and 11 hours in a wartime situation with a time of use of 24 hours a day, 7 days a week and 52 weeks a year. So these times are realistic for all possible scenarios.

2. Decision Orientated Variable Parameters

The variables shown in Table 4 on page 22 are the data upon which a decision
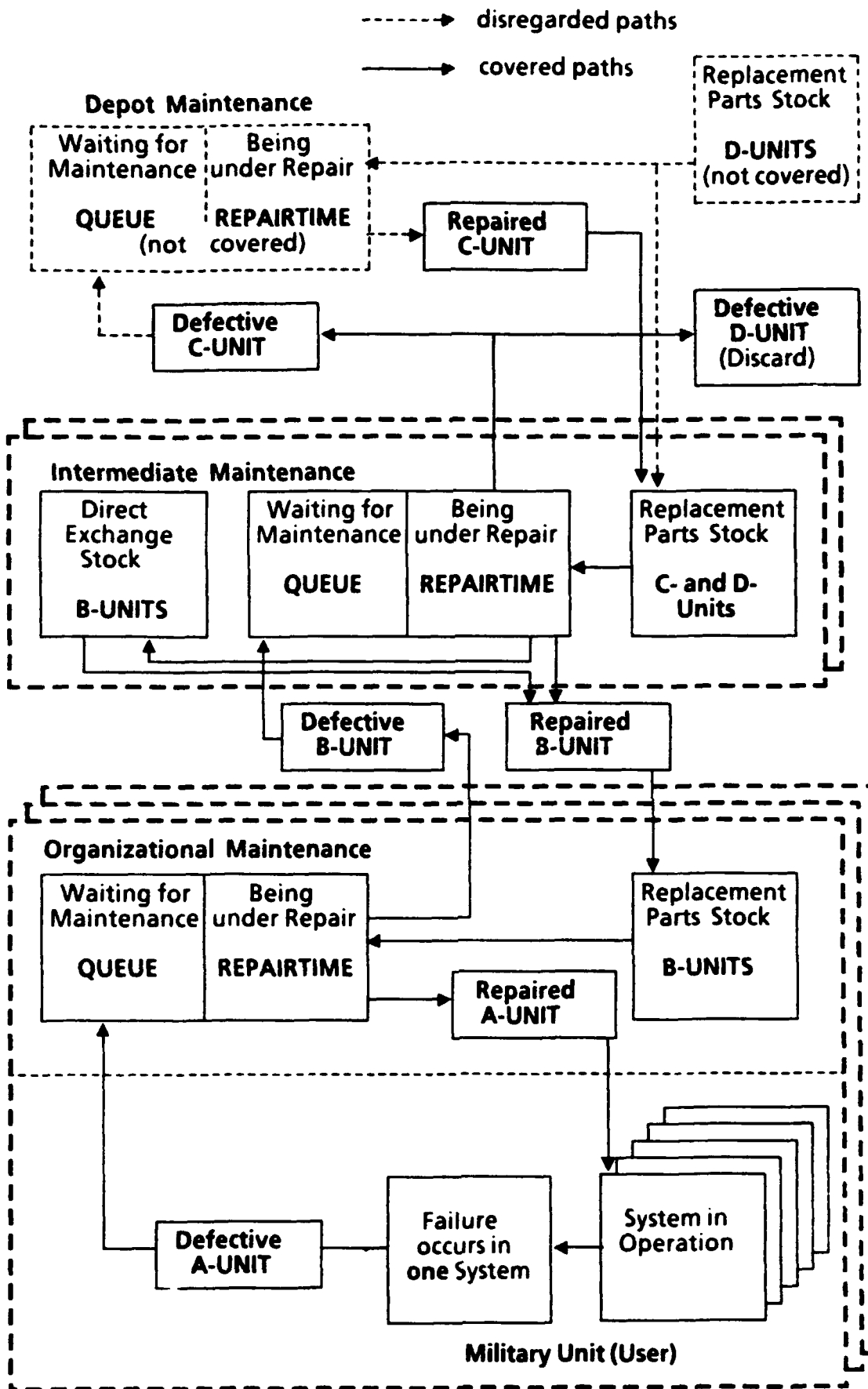
Figure 6.   Stochastic Model of the Maintenance System

Table 3. FIXED PARAMETERS OF THE MAINTENANCE SYSTEM

Parameter	Value (hours)	Description
S_{Total}	These data can be obtained from the current Acquisition Decision Memorandum (ADM)	Total number of systems deployed
S_{unit}		Number of systems deployed in one unit
U_D		Number of units per Division supplied with the system
D_C		Number of Divisions per Corps supplied with the system
U_C		Number of units under direct operational command of a Corps supplied with the system
$MART_A$	2	Mean Active Repair Time for an A-Unit by replacement of a B-Unit (see III.B.2.) or by performance of simple repair without replacement
$MART_B$	2 - 14	Active Repair Time for a B-Unit by replacement of C- and D-Units (error location and actual replacement) is dependent on the used technology
LDT_{stock}	1	Number of delay hours caused by logistic delay per repair job in all Maintenance Echelons if required spare part is in stock at maintenance facility
LDT_{DES}	10	Number of delay hours caused by logistic delay per repair job in Maintenance Echelon 2 if required Assembly has to be obtained from DES at Intermediate Maintenance
LDT_{supply}	35	Number of delay hours caused by logistic delay per repair job in Maintenance Echelon 3 if required spare part is not in stock, but available in the military supply line
ADT_2	2	Number of hours caused by administrative delay per repair job in Maintenance Echelon 2
ADT_3	35	Number of hours caused by administrative delay per repair job in Maintenance Echelon 3 (including transport times)

a decision has to be made. Realistic values will be chosen as initial input data[6], and will have to be readjusted for each new run of the simulation.

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6 What is realistic is determined by already known budgetary constraints, general personnel policies etc., and depends strongly upon the knowledge of an user experienced in his functional specialty.

Table 4. VARIABLE PARAMETERS OF THE MAINTENANCE SYSTEM

Parameter	Description
R_2	Number of repair personnel at Maintenance Echelon 2
$P_{2\,stock}$ (name)	Number of spare parts of component "name" in stock at Maintenance Echelon 2
R_{3D}	Number of repair personnel at Maintenance Echelon 3 (Division)
$P_{3D\,stock}$ (name)	Number of spare parts of component "name" in stock at Maintenance Echelon 3 (Division)
R_{3C}	Number of repair personnel at Maintenance Echelon 3 (Corps)
$P_{3C\,stock}$ (name)	Number of spare parts of component "name" in stock at Maintenance Echelon 3 (Corps)

3. Additional Variable Parameters

Some military performance requirements for a new system can be looked upon as variable parameters. If the required availability can not be achieved within the realistic range of the decision variables, reruns of the simulation with relaxed requirements can offer more insight into the problem. In Table 5 on page 22 the most important parameter of this kind is shown.

An example for this feature is any electronic device backed up by a mechanical device, where the electronic device may have $DT_{max} = 14$, whereas for example communication devices will generally have $DT_{max} = 0$.

Table 5. VARIABLE REQUIREMENT PARAMETERS

Parameter	Value (hours)	Description
$DT_{X\,max}$	Appropriate Value	Maximum allowable downtime for component "X" which will not decrease the operational capability of the system, and therefore will not count as a failure

D. REALIZATION OF THE IDEALIZED APPROACH

The applicability of the available closed form tools for the modeling and evaluating of the behavior of the complex modular structure of a new and mostly unknown electronic weapon system within the given three-echelon maintenance system of the German Army is limited in three ways:

1. It is a nightmare to apply the closed form tools for calculating the desired results under the assumption of Weibull- or Gamma-distributed Times Between Failures

2. Applying exponential failure rates will make the closed form calculations much easier, but too many assumptions have to be made, unreasonably simplifying the real world environment

3. Though a closed form calculation could be done by a computer program, this program will not be flexible enough for applications with different configurations.

The only way to proceed is the application of an open form method, the simulation of the complex real world situation. In simulating this situation it is generally assumed that

- A system is down when one component fails, and is up again when this component is replaced

- No aging takes places during downtimes

- For each repaired component a new time to next failure starts.

Using simulation we have to decide on the length of the time period simulated. This time period will be split up in

1. the phase used for determination of the reliability of the system (though we will not use it as a decision criterion)

2. a second phase up to the end of the time period, which is determined by war analysts to reflect a realistic war scenario (to obtain numerical values for spare part stocks at Organizational and Intermediate Maintenance facilities)

3. a third phase up to the end of simulation time, which has to be determined yet (to cover long-run aspects)

For illustration purposes we will introduce a Sample System in the next chapter (see Figure 8 on page 34). From the (fictitious) current ADM (Acquisition Decision Memorandum) for this Sample System we learn that the required time period for reliability considerations (the average system availability required is 90 %) is set to 175 hours, i.e. 5 weeks of peacetime or 1 week of wartime. So the length of the first time phase will be 175 hours.

Though the future NATO wartime scenario is about to be redefined after the end of the cold war, the "historical" value of 30 days of wartime is applied. So the end of the second time phase will be at 720 hours, resulting in a phase duration of 720-175 = 545 hours.

Special considerations are necessary to determine the appropriate total simulation time. Due to the fact that many components have a MTBF that is decisively greater than 720 hours, many of these components will not fail within the first two simulation time

phases, and might create the impression that they are not necessarily to be kept in stock. Another drawback is the fact that the Mean Time To First Failure (MTTFF) is always greater than the Mean Time Between Failures (MTBF), which causes the average availability and the expected MTBF to be computed with higher values than using a longer time period. To give each Subassembly and each Element the "chance to fail" within the simulation horizon, the total simulation time period should be chosen at a value some 10 times as large as the largest MTBF-value of any Subassembly or Element. With this method the computed availability of the system also asymptotically approaches the steady state value, because the initial MTTFF is dominated by an increasing number of MTBF-values used.

Consequently the time horizon for our Sample System will be 15230 hours (MTBF of Subassembly A02A = 1523 hours), divided in a first phase of 175 hours (to obtain a reliability value), a second phase of 545 hours (to obtain the necessary spare part stocks for a war scenario of 30 days), and a third phase with the remaining 14510 hours (to achieve the availability and the MTBF-value of the system in the long run).

IV. DEVELOPED AND APPLICABLE MULTI-ECHELON MODELS

A. EVALUATION OF EXISTING MULTI-ECHELON MODELS

Research among existing multi-echelon simulation models used by all branches of the U.S. Armed Forces showed that these programs are mainly aimed at the solution of the following problems [Ref. 19]:

- **Tie budget dollars to readiness.** This approach can not help in our case, because costs are unknown at the respective point of time in the acquisition process.

- **Determine the inventory levels required at each echelon of supply given a readiness objective.** This aspect comes closer to the problem to be solved, but it is based upon a given number of repair personnel. While this feature can help in the second part of the problem, it does not solve the **essential** problem of determining the number of repair personnel at each maintenance echelon.

- **Predict readiness given the inventory level at each echelon of supply.** Also this feature can not help in our case, because its basis are the numbers we need from the simulation.

Generally it is to be stated that all models concentrate on the supply side of the multi-echelon idea. As stated for the given problem in II.C.2.e., necessary stock levels are only considered as far as these stocks are located at the respective maintenance facilities. The three-echelon maintenance system represented by our stochastic model (see Figure 6 on page 20) is a closed environment, where the only link to the "outside world" is the replacement parts stock for D-Units at Depot Maintenance.

One way to proceed is the development of a new program that simulates the behavior of a weapon system with four indenture levels within the military environment of a closed three echelon maintenance system. But this task is far beyond the scope of a master's thesis. Another way to approach the problem is the application of one of these existing simulation programs under flexible use of the offered features close to the problem. One simulation program that is both applicable under this approach and available for use by a foreign student at the Naval Postgraduate School is the "TIGER Reliability Computer Program", developed and distributed for Government use by the NAVAL SEA SYSTEMS COMMAND, Washington D.C. [Ref. 20].

B. THE SIMULATION PROGRAM "TIGER"

TIGER is designed to calculate the mission performance parameters of ship system reliability and availability, and concentrates on the efficient supply with spares within

the Naval Supply System under consideration of available repair shop capacities and failure characteristics of the used equipment. It is in use in the US Army and US Air Force, too, and can be applied stepwise to obtain all the data which are needed to solve the given decision problem.

For use in this thesis, the program is first introduced with the problem relevant input and output options. Later the necessary sequence of steps in applying "TIGER" is developed using a sample system.

1. General Overview

The general objective of "TIGER" is the prediction of RAM (Reliability, Availability, Maintainability) performance of a general system, defined by data about the components within its indenture levels. "TIGER" is an event driven stochastic simulator [Ref. 20, p.2-5], and generates internally the following component events:

1. Failure of a component

2. Arrival of a spare part for a waiting component

3. Release of shop capacity for a waiting component

4. Repair of a component

The special features necessary to solve the given problem are listed below [Ref. 20, p.2-7 - 2-9], including first remarks about their sometimes limited applicability for the given problem.

- Gamma distribution for failures and delays, and exponential distribution for repair times: however, only integer β-values from 1 to 9 are possible (where $\beta = 9$ comes closest to a Normal distribution)

- Limited shop capacities; these shop capacities are the central decision parameters; however, the only shops considered are one "General Shop" and up to 20 specialty shops

- Allowable downtime; because not all components of a weapon system are essential for the mission performance, the failure of certain components can be tolerated for some time without being counted as system failure

- Group rules; using **string rules** all grouped components are turned off while the group is down due to failure of a specified control component 7, while **standby rules** take care of redundancies

- Logistic models; offering both spares inventory policy and unlimited spares

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7 In order to avoid excessive simulation run times the application of this rule is only appropriate, if $\dfrac{MTBF_{grouped\ components}}{MTTR_{specified\ control\ component}} \leq 50$ [Ref. 20, p. 5-2]

2. The Input Formats

The input formats are described in [Ref. 20, section 3]. To get an idea about the input structure, the relevant input formats needed to start a "TIGER" simulation are described below (the numbers indicate the respective TIGER input format):

1. Distinctive name of simulation (for later identification)

2. Number of Monte Carlo simulations; optional individual integer random seed

3. Time horizon of simulation; phase definitions for successive simulations under changing conditions and/or changing configurations (up to 6 phases in one simulation run)

4. - blank -

5. Selection of printout option

6. - blank -

7. Multiplier for all MTBF-values to model special conditions; multiplier for all MTTR-values to model special conditions; capacity of general shop; capacity of special repair shops

8. Component identification: user defined type number (between 1 and 200) and name for easier identification of maximal 200 different component types; MTBF; MTTR or indicator for not repairable item; LDT_{supply}; LDT_{stock}; probability that a repair requires a part at all (complementary probability that a failure can be fixed by simple methods); Gamma shape parameter for delay times; Gamma shape parameter for failures

9. - blank -

10. - blank -

11. - blank -

12. enumeration of all components used in the System (up to 500 components of the above defined 200 different types); a system in the way "TIGER" is used here can be a single unit of the Weapon System with components being Subsystems, or can be a military command level with components being military units using S_{unit} units of the Weapon System

13. - blank -

14. Indicator for unlimited spares or general number of spares (same number for each type of spare)

15. Individual number of spares per component (overrides format 14)

16. System definition (system in a general sense, not as an indenture level of an electronic system; from now on referenced as "TIGER system definition"); in contrary to the known or estimated components which are defined with type numbers 1 to 500 in format 8, in this and the two following formats the unknown System, the Subsystems and the Assemblies are defined with type numbers 501 to 1000.

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17. Subsystem definition (components building up System defined in format 16; from now on referenced as "TIGER subsystem definition"); allowable downtimes for these "TIGER subsystems"

18. Group definition (components building up the "TIGER system" and the "TIGER subsystems" defined in format 16 and 17, which are controlled by standby- and string rules (see IV.B.1)

19. Standby- and string rules

20. - blank -

21. - blank -

3. The Output Formats

"TIGER" offers a variety of output options. The output formats are listed and described below as far as they are relevant for the given problem:

1. Phase Figure of Merit Final Report [Ref. 20, p. 10-7] for the **entire** system

    a. Mean for reliability at the end of each time phase

    b. Mean for availability at the end of each time phase

2. Final Figure of Merit Summary [Ref. 20, p. 10-7] for the **entire** system

    a. Mean and variance for reliability at the end of the simulation time

    b. Mean and variance for availability at the end of the simulation time

    c. Mean and variance of the MTBF at the end of the simulation time

    d. Estimate of the long-term value of the availability

    e. Estimate of the long-term value of the MTBF

3. Subsystems Figures of Merit [Ref. 20, p. 10-7] for each **subsystem**

    • Average Availability at the end of each time phase

4. Component Performance Statistics [Ref. 20, p. 10-12]

    • Summary of spares used at the end of the simulation time

5. Critical Component List [Ref. 20, p. 10-12].

    • Contribution of each component type to the unavailability of the entire system and each subsystem

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V. THE DECISION MODEL

A. DECISION VARIABLES

As already discussed in III.C.2 and shown in Table 4 on page 22, the following decision variables have to be handled:

1. R_2, the number of repair personnel at Maintenance Echelon 2 (Organizational Maintenance)

2. $P_{2\,stock}$(B-Unit), the number of spare B-Units in stock at Maintenance Echelon 2

3. R_{3D}, the number of repair personnel at Maintenance Echelon 3 (Intermediate Maintenance) at Division level

4. $P_{3D\,stock}$(B-,C- or D-Unit), the number of spare B-, C- and D-Units in stock at Maintenance Echelon 3 at Division level

5. R_{3C}, the number of repair personnel at Maintenance Echelon 3 (Intermediate Maintenance) at Corps level

6. $P_{3C\,stock}$(B-,C- or D-Unit), the number of spare B-, C- and D-Units in stock at Maintenance Echelon 3 at Corps level

However, the way to obtain R_{3D} and $R_{3D\,stock}$ is the same as obtaining R_{3C} and $R_{3C\,stock}$ - they differ only in the number of weapon systems to be supported by one Maintenance Batallion. So in the further approach, which will develop the actual utilization of available tools, we will cover only R_2, R_3, $P_{2\,stock}$(B-Units) and $P_{3\,stock}$(B-, C- and D-Units).

B. INFLUENCE DIAGRAM

Due to the fact that there is no directly applicable simulation model for the given maintenance environment, we have to decide about the necessary steps in using the available programs. To gain insight into the decision problem structure, we develop an **Influence Diagram** , shown in Figure 7 on page 30.

1. Given Data

The only given data at the beginning of the decision process are

- The (rough) structure of the new Weapon System with
  - definition of functional units
  - level of used technology
  - redundancy concept
- The required Average System Availability
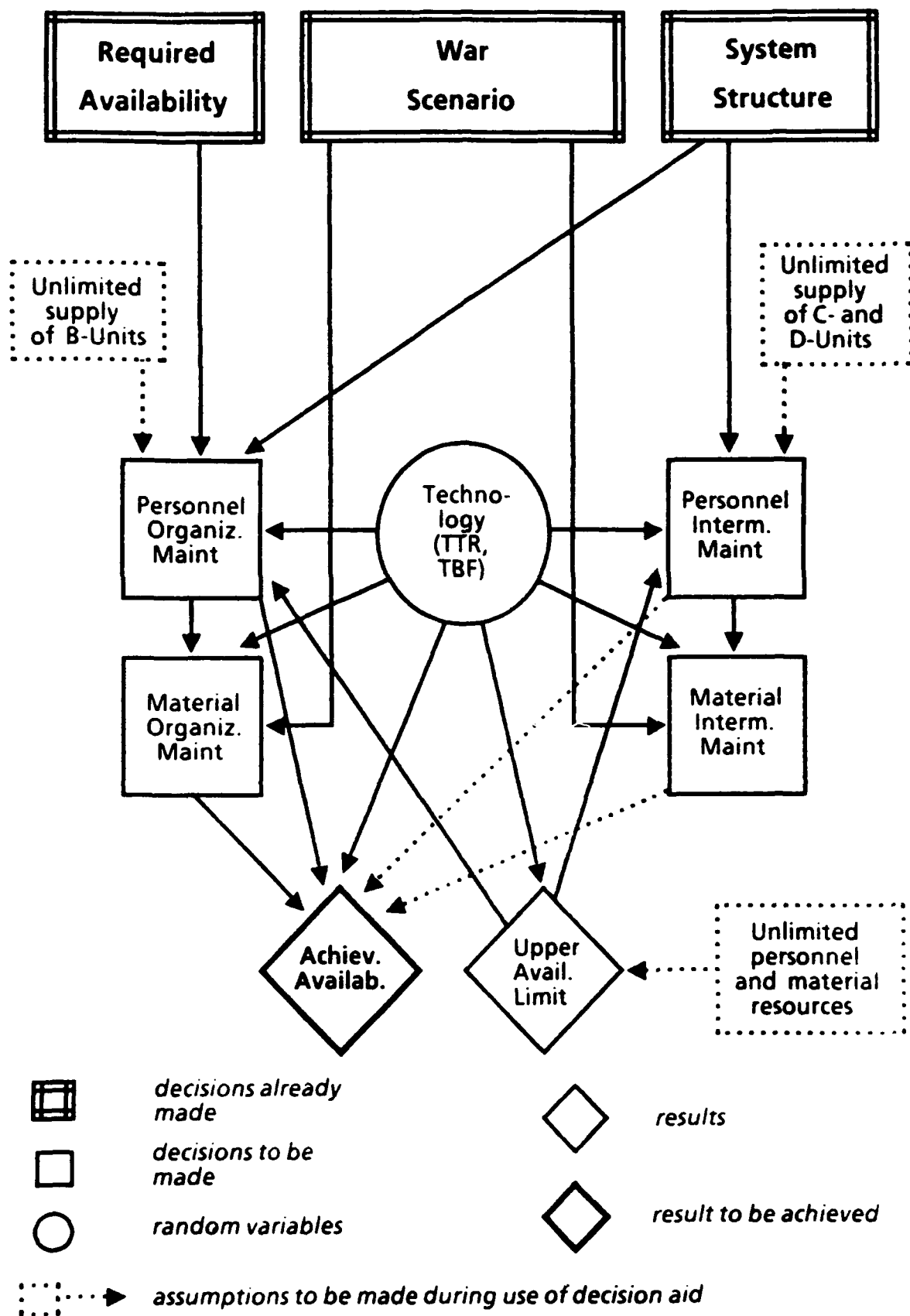
Figure 7. Influence Diagram for the Upcoming Decision

2. Available Data

For many already deployed systems the TBF- and TTR-values for Subsystems, Assemblies, Subassemblies and Elements are recorded and available. The functional characteristics of these evaluated components are known, also their technology level. Based on the given System Structure we can exploit similarities between components of the future system and known components. However, this link is not straightforward, and has the character of an assumption.

3. Direct Conclusions

Based on the used TTR- and TBF-values for the Subassemblies and Elements of the new system, and assuming unlimited personnel and materiel resources at Organizational Maintenance, we can obtain an Upper Availability Limit for one unit of the new system. This is a technology determined upper value, which can not be increased by any organizational decision or any other means.

4. Decision Variables

a. *Personnel in Organizational Maintenance*

Based on the System Structure, the required Average System Availability, the estimated TBF-values and the Upper Availability Limit, and under assumption of unlimited supply of B-Units at Organizational Maintenance, the consequences of certain numbers of repair personnel at Organizational Maintenance can be modeled and a decision based on an analysis can be made.

b. *Materiel in Organizational Maintenance*

Based on the available personnel at Organizational Maintenance (= the number decided upon), the estimated TBF-values and the underlying war scenario, the consequences of certain stock levels of B-Units at Organizational Maintenance can be modeled and a decision based on analysis can be made.

c. *Personnel in Intermediate Maintenance*

Based on the System Structure, the estimated TBF-values and the Upper Availability Limit, and under assumption of unlimited supply of C- and D-Units at Intermediate Maintenance, the consequences of certain numbers of repair personnel at Intermediate Maintenance can be modeled and a decision based on an analysis can be made.

d. *Materiel in Intermediate Maintenance*

Based on the available personnel at Intermediate Maintenance (= the number decided upon), the estimated TBF-values and the underlying war scenario, the

consequences of certain stock levels of B-, C- and D-Units at Intermediate Maintenance can be modeled and a decision based on analysis can be made.

5. Final Conclusion

Based on the personnel and materiel quantities at Organizational Maintenance, and under assumption of sufficient personnel and materiel quantities at Intermediate Maintenance (= the numbers decided upon), the Maximum Achievable Average System Availability under the quantified Maintenance System can be checked versus the Upper Availability Limit.

VI. SIMULATION WITH THE TIGER PROGRAM

At first the preparative structuring of the new Weapon System for the input process is described, followed by the essential input steps for each successive simulation run. The applicability of the respective results for our decision problem is shown, and the reasoning for the next input step is derived.

A. PREPARATIVE STRUCTURING OF THE WEAPON SYSTEM

To simplify the illustration of the use of "TIGER" in solving the given problem, and to show the emerging results and their consequences, the program is applied to the simple yet complete Sample System configuration shown in Figure 8 on page 34.

In contrast to the "TIGER" concept only very few components (if any at all) shown in our Sample System configuration have known TBF and TTR. Proceeding down from the **System level**, and skipping the **Subsystem level**, all Assemblies are checked for available MTBF-data, β-values for the distribution of the TBF and MTTR-data:

1. If there are no real data available for an Assembly, we proceed further down and check the Subassemblies and those Elements which are not a direct part of a Subassembly. Elements within a Subassembly are only handled by depot level maintenance, which is not covered here (see I.D.3)

   a. If we have real data for a Subassembly or an Element, which might be in use in an already deployed weapon system, these data are applied

   b. If there are no real data available, data from a component with **similar functional characteristics** and a **comparable level of technology** are applied

   c. In case of several similar components with different parameters or in case of components with a totally new conceptual design, the best possible estimates [8] have to be applied

2. If we have real data from an Assembly, which is in use in an already deployed weapon system, the Assembly itself is treated as an unknown, but with exactly one known Subassembly

3. As a further preparation for the input the known or estimated Subassemblies and Elements are assigned a type number between 1 and 500, all unknown Subsystems and Assemblies a number between 501 and 1000. One possible choice for assigning these numbers is shown in Figure 8 on page 34.

At the end of this process each branch of the configuration tree ends with a component for which the MTBF, β and MTTR data are fixed. Because we do not have any

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[8] Again, the user has to be experienced in his functional specialty

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999 | **SAMPLE SYSTEM** — (Maximum allowable downtime $DT_D = 35$)

Subsystems: A 50i, B 610 601, C 701, D 801

611/612

510 A01, B01, C01, D01 810

520 A02, 620 B02, 720 C02, D02 820

Assemblies: 530 A03, 730 C03, D03 830

Subassemblies (XXXA etc.) and Elements (XXX01 etc.) — C03A

11 | MTBF = 1327, ß = 3 / A01A MTTR = 4.1
13 | MTBF = 841, ß = 9 / A02A MTTR = 3.6
15 | MTBF = 344, ß = 9 / A03   MTTR = 1.5

12 | MTBF = 644, ß = 9 / A01B MTTR = 3.9
14 | MTBF = 1523, ß = 9 / A0201 no repair

known assembly

21
2 redundant (22) assemblies 23 (24)

21 | MTBF = 225, ß = 1 / B0101 no repair
25 | MTBF = 866, ß = 7 / B0201 no repair

23 | MTBF = 534, ß = 9 / B0102 no repair
26 | MTBF = 1167, ß = 5 / B02A MTTR = 13.8

31 | MTBF = 544, ß = 9 / C0101 no repair
33 | MTBF = 1322, ß = 9 / C02A MTTR = 3.8
35 (36) | MTBF = 210, ß = 9 / C03A MTTR = 8.4

32 | MTBF = 732, ß = 7 / C0102 no repair
34 | MTBF = 1003, ß = 4 / C02B MTTR = 9.5
(37)

3 redundant subassemblies

41 | MTBF = 375, ß = 5 / D01A MTTR = 1.5
44 | MTBF = 554, ß = 5 / D02A MTTR = 7.2
46 | MTBF = 628, ß = 2 / D03   MTTR = 2.3

42 | MTBF = 445, ß = 9 / D01B MTTR = 4.1
45 | MTBF = 1303, ß = 3 / D0201 no repair

known assembly

43 | MTBF = 1127, ß = 8 / D01C MTTR = 22.6

Figure 8. Sample System Configuration (Prepared for Input)

information about interdependencies between components at this stage of the development process, we assume that there are none at the moment. Components with stand-by redundancies (groups of components, where in case of failure of the active component another component starts operating) are grouped using the TIGER stand-by rule; generally string rules will not be applied, because for electronic equipment with high reliabilities and short repair times the MTBF/MTTR-quotient (see footnote 7 on page 26) will mostly be considerably higher than 50.

B. MAXIMUM AVERAGE WEAPON SYSTEM AVAILABILITY

The input file for the first simulation step lists all Subassemblies and Elements with their (known or estimated) individual MTBF- and β-values to determine the failure characteristics of the entire (unknown) system. Each failure of any component initializes the repair of the failed A-Unit (Subsystem) by replacing the failed B-Unit (Assembly within the failed A-Unit). This repair time can be assumed to be relatively constant due to the technology used (BITE etc., see Table 1 and Table 3, $MART_A$). Starting with the general maintenance system, i.e. without applying any exceptional regulations, we will obtain the maximum achievable availability under ideal conditions by assuming both unlimited shop capacity and unlimited supply of spare B-Units at Organizational Maintenance. Because, at this point of time, we do not need any information about spare parts used, we do not need to record the results of the second time phase (see III.D.).

To gain more insight into the Maintenance of the new Weapon System, we additionally consider 2 methods for increasing the numerical value of the maximum possible average system availability:

- **Relaxed Tactical Requirements.** The Mission Need Statements (MNS), which initialize the acquisition process for a new weapon system, tend to require an availability of a weapon system close to 100% with no allowable downtimes for any Subsystem. In many projects this goal can not be achieved even under the ideal approach described above. Therefore allowable downtimes for selected Subsystems are additionally entered. **It is essential to point out, that the quality of the weapon system is not improved at all by this means - it is just a statistical improvement aimed at the purpose of the decision aid !**

- **Exceptional Spare Stock of A-Units (Subsystems) at location of Organizational Maintenance.** Now an unlimited spare stock of A-Units at the organizational level is allowed, actually reducing the mean delay time until resuming operation.

1. Step 1, Run 1 - System in the General Maintenance System

For the first step one unit of the Weapon System is defined in a format 16 statement ("TIGER system definition"), and all Assemblies, Subassemblies and Elements are assigned to their respective Subsystem under format 17 ("TIGER subsystem defi-

nition"). Strictly following the rules (see II.D.1. - no spare stock of A-Units at the organizational level), the resulting mean delay time until resuming operation is $MART_A + LDT_{Stock} + ADT_2 = 5$, given the required B-Unit is available at the replacement parts stock of the Organizational Maintenance. Due to the "fixed" repair time of 5 hours this value is entered as "real organizational delay", while the MTTR-values for all Subassemblies and Elements are set to 0.001 (Tiger default value). This method is necessary to neglect any repair times for these components, which are irrelevant in this first step. Without regarding any eventually allowable downtimes, the results of the first simulation run offer a set of data based on the **technology** used and on the **unmodified general maintenance system**. Any possible real-world logistic delays could not happen due to assumption.

The following results are determined from the first run:

- *Upper limit for Average System Availability under consideration of technology and general maintenance system.* Without any exceptional regulations within the general maintenance system no higher value for the average availability can be achieved.

- *MTBF for one unit of the System under the conditions stated above*

- As additional information we obtain the *Reliability* for the time period entered as first phase duration. But as pointed out above (see III.B.4.), reliability can not be used as a criterion for the upcoming decision, and therefore will be tracked only occasionally.

The relevant results for our Sample System (for this and the next three runs) are listed in Table 6 on page 38.

2. Step 1, Run 2 - System under Relaxed Tactical Requirements

In many projects the desired availability can not be achieved even under the ideal approach modeled in Run 1. Therefore the second run additionally regards allowable downtimes for selected Subsystems under tactical considerations.

The results of the second run offer:

- *Tactically Increased Upper Limit for Average System Availability* . By allowing downtimes for not-operationally-essential Subsystems, the technology determined upper limit for the average availability of each unit of the Weapon System will be increased once more, offering insight into the consequences of tight requirements.

- *MTBF for one unit of the System under the conditions stated above*

The MTBF-value should be decisively higher than that in Run 1 (less failures counted for calculation of down time).

3. Step 1, Run 3 - System in Modified Maintenance System

For the third run one unit of the Weapon System is defined in the same way as in Step 1. But now an unlimited spare stock of A-Units at the organizational level is allowed, reducing the mean delay time until resuming operation to $LDT_{stock} + ADT_2 = 3$. This value is now entered as "real organizational delay", while the MTTR-values are kept at 0.001. Assuming unlimited shop capacity and no allowable downtimes again, an ideal (modified) logistic environment is modeled - the results of the third run offer a set of data based on the technology used and represent the maximum achievable average availability of the planned Weapon System in the three echelon maintenance system under exceptional regulations.

The following results are offered from the third run:

- *Technology determined absolute upper limit for Average System Availability.* With no organizational or any other means can any higher value for the average availability be achieved within the given maintenance system.

- *MTBF for one unit of the System under the conditions stated above* (should be close to the MTBF-value obtained from Step 1, Run 1 - differences due to simulation)

4. Step 1, Run 4 - System Behavior under Both Methods

As described for Step 1, Run 2, additionally allowable downtimes for selected Subsystems under tactical considerations are entered. The results of the fourth run offer:

- *Tactically increased absolute upper limit for Average System Availability*

- *MTBF for one unit of the System under the conditions stated above* (should be close to the MTBF-value obtained from Step 1, Run 2 - differences due to simulation)

5. Evaluation of Step 1

The requirements and the relevant results from Step 1 for the given Sample System are summarized in Table 6 on page 38.

The standard deviation for all $\overline{A}$-values obtained by simulation is 0.000, pointing out that at $t = 15230$ we obviously have reached a steady state. Dependent on the required availability and the results, some options for the further approach might no longer be reasonable. In our example, no stock of A-Units at the location of the Organizational Maintenance has to be considered, because the required availability of 90 % can be achieved under the allowable-downtime approach[9].

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9 These results also offer insight into the consequences of too tight tactical requirements, which might drive up costs if accepted without analysis

Table 6. MAXIMUM ACHIEVABLE SYSTEM AVAILABILITY

	Average Availability	$M\hat{T}BF$	$\hat{R}$	$M\hat{T}TFF$
Requirement	$\overline{A} = 0.900$			
No stock of A-Units, no allowable downtimes	$\hat{\overline{A}} = 0.892$	43.6	0.696	227.2
No stock of A-Units, relaxed requirements	$\hat{\overline{A}} = 0.934$	72.3	0.924	299.2
Unlimited stock, no allowable downtimes	$\hat{\overline{A}} = 0.934$	43.8	0.700	214.0
Unlimited stock, relaxed requirements	$\hat{\overline{A}} = 0.960$	72.6	0.928	292.3

So the further approach uses the environment modeled in Run 2. The input file for Run 2 is shown completely in Appendix A, and the resulting output for Step 1, Run 2 is shown partially (without computer system messages, input echo and an error message[10]) in Appendix B.

C. PERSONNEL QUANTITIES AT ORGANIZATIONAL MAINTENANCE

Still under the assumption of an unlimited stock of B-Units, the unlimited repair capacity at Organizational Maintenance will be reduced now to realistic values. To model this situation, a new approach is needed, using MTBF-values of all Subsystems, and regarding the entire military user unit. We do not need information about spare parts used nor about the reliability of the subsystems. Therefore we do not record the results of the first two time phases.

1. Step 2, Run 1 - MTBF-Values for Subsystems

To obtain these MTBF-values, each Subsystem is defined in a format 16 statement ("TIGER system definition") and as only Subsystem under format 17 ("TIGER subsystem definition"), while all its Subassemblies and Elements are assigned to this one Subsystem. The environment for these simulation steps assumes no stock of A-Units at Organizational Maintenance, and no allowable downtimes are entered to obtain the technology determined MTBF. The repair shop capacity is without influence on the re-

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10 TIGER calculates the reliability for $t = 15230$ as $R < 16^{-65}$ and causes a "Floating Point Underflow Exception"; using "Standard Corrective Action", the value of R is set to 0.000, and the program completes correctly

sult of Run 1, and is kept unlimited. One run for each Subsystem has to be performed. The following result is offered from the first run:

- *Technology determined MTBF-Values of all Subsystems*

Due to the characteristics of the TIGER simulation these values are offered without any distribution parameters. In order to avoid unrealistic simplification by using the mean values only, the generally accepted assumption of exponential distribution for time between failure (see III.A.1) will be used for further computations.

For our Sample System the following results are obtained:

Table 7. MTBF-VALUES FOR SUBSYSTEMS

Subsystem	$M\hat{T}BF$	$\hat{\sigma}_{simulation}$	$\hat{\bar{A}}$
A	145.7	6.513	0.966
B	471.3	6.470	0.990
C	206.0	7.035	0.976
D	110.3	6.073	0.956
Entire System	72.30	6.150	0.934

2. Step 2, Run 2 - Minimum Personnel Quantity, Unlimited Stock

Starting with personnel quantity of 1 (the minimum value - see II.D.1), we define the military unit in format 16 ("TIGER system definition"), consisting of S_{unit} sets of all Subsystems. For our Sample System we learn from the (assumed) ADM that each military unit has S_{unit} = 17 units of the Weapon System. The MTTR is 2 hours (see Table 3); the stock of B-Units is unlimited; the delay time is $LDT_{stock} + ADT_2 = 3$ hours. Due to the characteristics of TIGER the "allowable downtime" approach is not applicable in this data input configuration - allowable downtimes can be entered only for "TIGER subsystems" (here the 17 weapon systems). That means for our Sample System that the maximum achievable Average System Availability will be 0.892 (subject to deviations due to simulation) instead of 0.934, which has to be considered in evaluating the output and deciding upon the personnel quantity.

Because we are primarily not interested in the "TIGER system" availability (the "availability" of one military unit), but in the availability of each unit of the Weapon System (the "TIGER subsystem" availability), the output option for subsystems has to

be chosen. Nevertheless, defining the military unit as available (combat ready) if 15 out of 17 weapon systems are up, we will have a glance at this value.

The following result is offered from the second Run:

- *Upper limit for Average System Availability at minimum personnel quantity at Organizational Maintenance*

3. Step 2, Run 3 - Increased Personnel Quantity, Unlimited Stock

If the resulting upper limit for the Average System Availability is insufficient, further runs with incremented personnel quantities (up to a **realistic** limit) have to be performed, eventually resulting in the

- *Upper limit for Average System Availability for personnel quantity of 2 at Organizational Maintenance*

- *Upper limit for Average System Availability for personnel quantity of 3 at Organizational Maintenance*

- ...

- ...

- *Upper limit for Average System Availability at maximum personnel quantity at Organizational Maintenance*. For our Sample System the maximum realistic personnel quantity is assumed to be 4.

For our Sample System the resulting upper limits for the Average System Availability for one unit of the Weapon System with a given personnel quantity and an unlimited stock of B-Units at the location of the Organizational Maintenance are shown in Table 8.

Table 8. PERSONNEL AT ORGANIZATIONAL MAINTENANCE

Quantity of Personnel	Maximum Average System Availability	Availability of the Military Unit
1 (= minimum)	$\mu = 0.813, \sigma = 0.0006$	0.453
2	$\mu = 0.888, \sigma = 0.0005$	0.706
3	$\mu = 0.893, \sigma = 0.0004$	0.731
4 (= maximum)	$\mu = 0.894, \sigma = 0.0005$	0.731
Threshold	0.892	---

4. Evaluation of Step 2

As a general rule the smallest value for the personnel quantity, which provides the desired numerical availability value[11], will be used for all further computations. However, the data base used for these calculations is not exact at all - most values are (and will be in later applications) very rough estimates. So it is the responsibility of the **experienced** user, to decide about the appropriate personnel quantity. In our case quantity 1 provides an Average System Availability of 0.813 versus the maximum availability of 0.892 (equivalent to 91.1 %), quantity 2 provides 0.888 (equivalent to 99.6 %), and quantity 3 even offers 0.893, which can be considered as being the maximum value (again, deviations caused by simulation). For our Sample System, quantity 2 will be used further on.

If even the realistic maximum number of repair personnel is insufficient to achieve the desired numerical availability, the introduction of an exceptional stock of A-Units at Organizational Maintenance might be regarded by repeating Step 2 not based on Step 1, Run 2, but on Step 1, Run 3 or 4.

If under the assumption of an unlimited stock of B-Units a certain personnel quantity is sufficient, this quantity can be looked upon as the maximum quantity necessary. But this personnel can not utilize an unlimited stock. Consequently the unlimited stock of B-Units at Organizational Maintenance should now be reduced to realistic values, applying the personnel quantity obtained in Step 2.

D. MATERIEL QUANTITIES AT ORGANIZATIONAL MAINTENANCE

As pointed out in II.C.2.e., stock levels will only be considered as far as they are located at the facilities of the respective Maintenance Echelon. So now we need to know how many units of each B-Unit should be held at each location of Organizational Maintenance. The main reason for keeping this stock at all is the chance to increase the Achievable Average System Availability during combat. The second time phase (as defined in III.D.) becomes relevant now, and due to the output characteristics of TIGER (summary of spares used at the end of the simulation time - see IV.B.3.4) the simulation time horizon is now reduced to 720 hours.

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11 See the discussion about the application of the "allowable downtimes" idea for this simulation step in VI.C.2.

1. **Step 3, Run 1 - Maximum Number of Spare Parts Used in War Scenario**

Applying the personnel quantity obtained by Step 2, Run 2 or 3, we simply repeat the respective simulation run with decreased time horizon. The "unlimited spares" option is kept in the input file to prevent any supply from outside. The result of this **repeated run** will be the

- *Upper Limit for Spare Parts needed at Organizational Maintenance in the Applied War Scenario*

If every failure results in the replacement of the respective B-Unit by personnel of Organizational Maintenance, this is the maximum number of spare parts needed during the war scenario. By setting the "spares allowance" for each Assembly individually to the smallest integer being greater than the computed values, while still assuming unlimited supply at the intermediate level DES, we will obtain from Step 3, Run 1 the Maximum Average System Availability achievable with this stock level. Because some parts will now be used out of the Intermediate Maintenance DES - some simulation runs need more than the average number of spare parts - we additionally enter LDT_{DES} = 10 hours, the delay time to obtain spare parts from the DES.

2. **Step 3, Run 2 - Consequences of Lower Allowances**

With the above values being upper limits, we want to analyze the consequences of lower allowances now. The only drawback of lower stock levels is the increased logistic delay time due to supply out of the DES of the respective Maintenance Batallion. Instead of checking each combination of decreased allowances, we set **all** allowances at Organizational Maintenance to Zero, and keep the stock level at the Intermediate Maintenance DES unlimited, thus obtaining the

- *Upper Limit for Spare Parts needed at the Intermediate Maintenance DES in the Applied War Scenario*

- *Upper Limit for the Achievable Average System Availability with Zero Stock Allowance at Organizational Maintenance*

3. **Step 3, Run 3 - Consequences of Zero Stock Allowances**

In economically tough times even the necessity of any stock levels outside the military supply line might be in doubt. To be able to present data for this situation, we finally set both the stock level at Organizational Maintenance and at the Intermediate Maintenance DES to Zero (setting the DES to Zero with stock of Organizational Maintenance at upper limit will not change the results from Run 1, because only an average of 3 or 4 Assemblies will be used from the DES). Repeating Run 2, but replacing

the 10 hour delay (for receiving the needed Assembly from the respective DES) by a 35 hours delay (for the use of the military supply line), we obtain

- *Upper Limit for the Achievable Average System Availability with Zero Stock Allowance*

The results of Step 3, Run 1 to 3 are summarized in Table 9.

Table 9. MATERIAL AT ORGANIZATIONAL MAINTENANCE

Modeled Stock Levels(O = Org Maint, I = Interm Maint)	Allowance at OrgMaint (Assembly A/B/C/D)	Allowance at IntermMaint DES (Assembly A/B/C/D)	Maximum Average System Availability	B-Units obtained from Intermediate Maintenance DES (Assembly A/B/C/D)	B-Units obtained from Supply line (Assembly A/B/C/D)
Upper Limit at O, unlimited DES at I	101/32/73/134	unlimited	**0.885**	4/3/3/3	0/0/0/0
Zero at O, unlimited DES at I	0/0/0/0	unlimited	**0.765**	97/32/70/125	0/0/0/0
Zero at O, Zero DES at I, unlimited supply	0/0/0/0	0/0/0/0	**0.477**	0/0/0/0	84/30/63/104
Threshold	-	-	0.888	-	-

4. Evaluation of Step 3

All calculations in Step 3 have been performed under the assumption that available stocks are not refilled during the time period set by the applied war scenario. Nevertheless unlimited supply of spare parts at the respective source was used in the simulation runs. While this method was used in Run 1 and 2 just as a tool to obtain the maximum stock levels at Organizational Maintenance and the Intermediate Maintenance DES, the use of the unlimited supply line (see assumption stated in II.C.2.e.) was realized in Run 3 and 4 to model the situation of Zero allowances.

Evaluating the data displayed in Table 9, consequences of cuts proposed in budgetary discussions can be demonstrated based on analysis rather than on pure and not necessarily wrong, but improvable intuition. Pertaining to **numerical numbers for**

optimal stock levels at Organizational Maintenance and Intermediate Maintenance DES, we need more information about the back flow of repaired components, which are used to refill both the stock at Organizational Maintenance and the DES at Intermediate Maintenance during the simulated time period.

E. QUANTITIES AT INTERMEDIATE MAINTENANCE

Entering the intermediate level, the environment is similar to that modeled for the organizational level; however, the objects for repair are now Assemblies (B-Units). These B-Units fail as described above, are replaced by the Organizational Maintenance, and finally arrive some time after failure at the Intermediate Maintenance. TIGER does not offer any links between Organizational and Intermediate Maintenance; so we can not simulate the exact arrival times. But we can model this delay time by modeling the arrival at Intermediate Maintenance at the time of failure, and covering the delay time by $ADT_3 + LDT_{Stock}(\text{Organiz.}) + LDT_{Stock}(\text{Intermed.}) + ADT_2 = 39$, the number of hours caused by administrative and logistic delay per repair job in Maintenance Echelon 3 (see Table 3 on page 21) plus the delay time occurred in Organizational Maintenance while replacing the defective B-Unit. Under the assumption of an unlimited stock of C- and D-Units, we first have to obtain the MTBF-values of all Assemblies, and then have to model all subordinate military units served by the Maintenance Batallion. For our Sample System we learn from the (fictitious) ADM, that each Corps will have three Divisions using the new Weapon System, and that each Division will have 3 Brigades, each commanding 2 Military Units supplied with 17 Weapon Systems each. Referring to Table 2 on page 12, each Maintenance Batallion at the Division level will service 102 Units of the Weapon Systems.

1. Step 4, Run 1 - MTBF-Values for Assemblies

To obtain these MTBF-values, each Assembly is defined in a format 16 statement ("TIGER system definition") and as only component under format 17 ("TIGER subsystem definition"), while all its Subassemblies and Elements are assigned to this one Assembly. No downtimes are applied, and any repair shop capacity is kept unlimited. One run for each Assembly has to be performed. The following result is offered from the first run:

- *Technology determined MTBF-Values of all Assemblies*

As discussed in VI.C.1., the generally accepted assumption of exponential distribution for time between failure will be used for further computations.

The results for our Sample System are shown in Table 10 on page 45.

Table 10. MTBF-VALUES FOR ASSEMBLIES

Assembly	$\widehat{MTBF}$	$\hat{\sigma}_{simulation}$	$\hat{\bar{A}}$
Assembly A01	455.6	8.357	0.989
Assembly A02	563.4	8.669	0.991
Assembly A03	344.0	MTBF is given	0.986
Subsystem A	145.7	6.513	0.966
Assembly B01	161.4	7.429	0.970 (2 redundant Assemblies in Subsystem))
Assembly B02	511.0	8.749	0.990
Subsystem B	471.3	6.470	0.990
Assembly C01	321.1	8.088	0.985
Assembly C02	587.0	8.672	0.991
Assembly C03	3807500	0.000	1.000 (3 redundant subassemblies)
Subsystem C	206.0	7.035	0.976
Assembly D01	175.6	6.689	0.972
Assembly D02	563.7	8.995	0.991
Assembly D03	628.0	MTBF is given	0.992
Subsystem D	. 110.3	6.073	0.956
Entire System	72.30	6.150	0.934

2. Step 4, Run 2 - Minimum Personnel Quantity, Unlimited Stock

a. *Approach as Proved in Step 2*

So far the new Weapon System could be treated without regarding different fields of technology. MTBF-values are computationally independent from the used technology, and the personnel at Organizational Maintenance could be planned across the fields of technology due to the way they are supposed to perform: localize defective LRU by using BITE or straightforward traditional techniques, and replace them. At Intermediate Maintenance however, personnel for all different fields of technology have to be available. To show the modeling of this situation, we assume that our new Weapon System is made up of four different fields of technology, resulting in the use of 4 "TIGER specialty shops".

We start with personnel quantity of 2 (the minimum value - see II.C.2.b.), defining the Division in format 16 ("TIGER system definition"), consisting of $U_D S_{unit}$ sets of the number of Assemblies used per System. Each Assembly is defined by its Subassemblies and Elements, and the MTTR for each Assembly is determined by the used technology (see III.B.2. and Table 3 on page 21). The stock of C- and D-Units is assumed to be unlimited.

For our Sample System $U_D S_{unit}$ = 102, resulting in 1224 "TIGER subsystems"; the (assumed) MTTR for the different technologies are 7 (Subsystem A), 4 (Subsystem B), 12 (Subsystem C) and 3 (Subsystem D). The delay time is 39 hours.

b. Dimensional Problems

At this point we are about to run into dimensional trouble with TIGER. Table 11 compares the dimensional needs to perform Step 2, Run 2 (Personnel at Organizational Maintenance) and Step 4, Run 2 (Personnel at Intermediate Maintenance) with the capacity of TIGER.

Table 11. DIMENSIONAL PROBLEMS WITH "TIGER"

Data	Capacity needed (Step 2)	Capacity needed (Step 4)	Capacity offered
Number of distinct Subsystems	17	1224	31
Number of Component types	20	20	200
Number of distinct Components	68	2040	500

First of all, I want to emphasize that this is not the fault of the TIGER program !. As pointed out in IV.A., Tiger is one of the available simulation programs, and in this application it has not been used in the way it was designed. It is moreover a sign of the versatility of TIGER that it could be used so far in such a successful way. But we will run into trouble even earlier, if we want to model electronic material of the combat troops. As discussed in II.C.1., combat units have a large number of identical equipment. If we try, for example, to obtain data for the maintenance concept for the electronic components of a battle tank - in general an Armored Batallion has 52 battle tanks (52 TIGER subsystems in Step 2 versus the capacity of 31 subsystems) -, we can not use the described approach.

c. Goal to be achieved by Intermediate Maintenance

Another problem arises in defining the optimality criterion for Step 4, Run 2. In Step 2 the goal to be achieved was clearly defined: keep the Average System Availability at or above the numerical value required by the ADM ! We could use this criterion if TIGER would offer the feature of refilling any stocks with components repaired within the Maintenance System. Due to the origin of TIGER in the Navy, the general shop (and eventually involved special shops) repair the Weapon System as a whole under the environment of a **Three Echelon Supply System.** There is no repair of defective components performed to refill stock levels - TIGER does not model a **Three Echelon Maintenance System !**

Though even if we would be able to handle the dimensional problem, this missing link will make it impossible to proceed further on with the use of TIGER.

VII. FURTHER APPROACH USING MODSIM

Being unable to complete our decision aid with TIGER, we now attack the problem with the same approach, but applying the simulation language MODSIM II, which came to my knowledge only in the last Quarter at NPS. As far as this Thesis is concerned, only initial feasibility checks are performed. The development of a complete simulation program has to be done by follow-on research.

A. REDUCED STOCHASTIC MODEL

Applying the TIGER simulation program (see VI.), we have realized that all data necessary to solve the given problem can be obtained without modeling the entire stochastic model shown in Figure 6 on page 20. Thus we will use a reduced stochastic model for the remaining parts of the problem (shown in Figure 9 on page 49).

The only parts of the initial stochastic model to be considered are:

1. Structured Weapon System with its
   a. Subsystems
   b. Assemblies
   c. Subassemblies
   d. Elements
2. Organizational Maintenance with its
   a. Waiting Queue
   b. Repair Capacity
   c. Stock of B-Units for replacement
3. Intermediate Maintenance with its
   a. Waiting Queue
   b. Repair Capacity
   c. Direct Exchange Stock
   d. Stock of C- and D-Units for replacement (**assumably unlimited**)

The sequence of steps will be the same as with TIGER, as this approach has been proved to be adequate and successful. Upon final development of the problem specific MODSIM simulation program, the results for our Sample System obtained by TIGER can be cross checked with the values obtained by MODSIM.
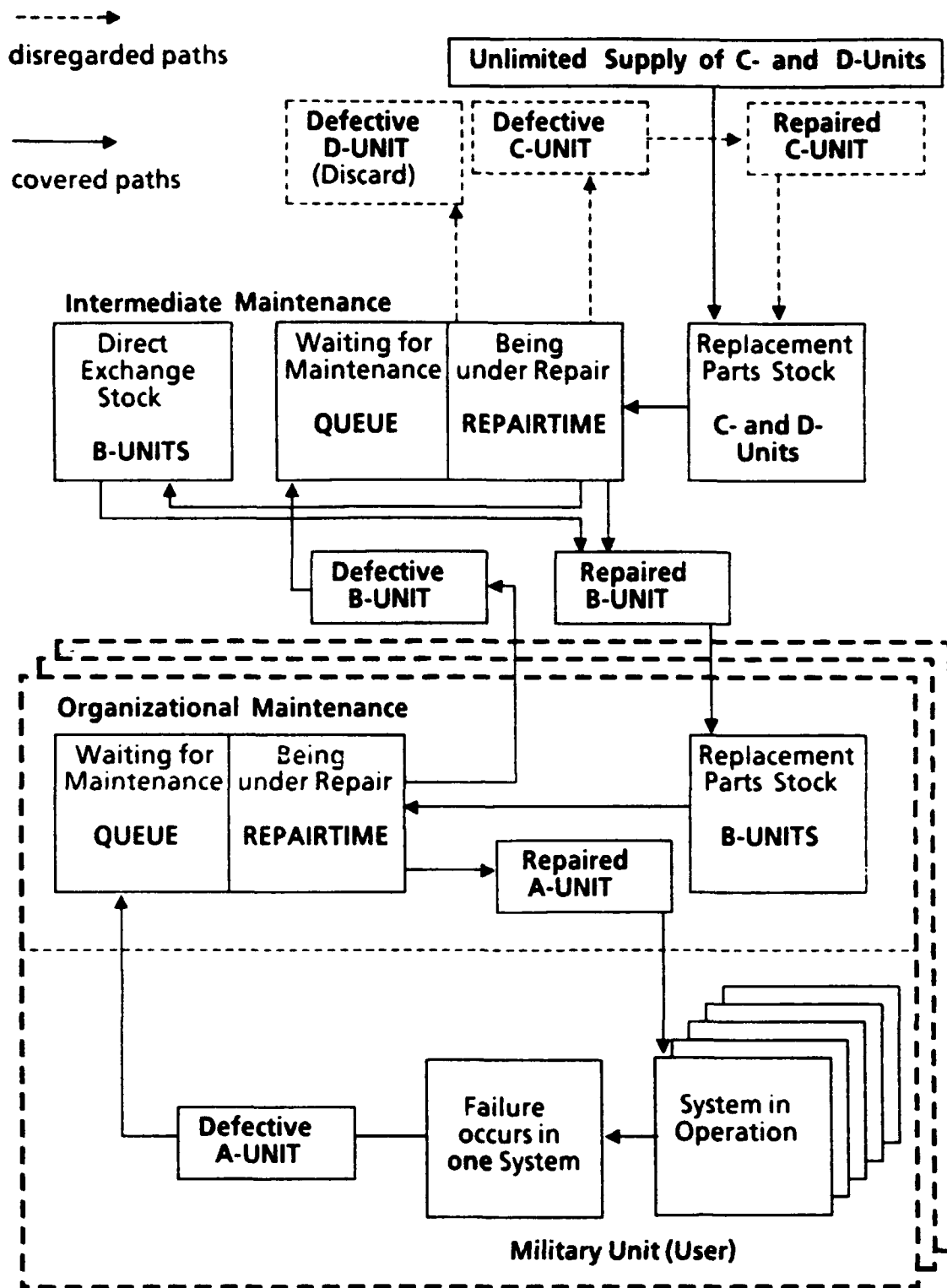
Figure 9. Reduced Stochastic Model

B. MODSIM II - GENERAL OVERVIEW

MODSIM-II is a general-purpose, procedural programming language [Ref. 21]. It is an **object-oriented** language, and it performs **discrete-event simulation**. Like in real world, each object has

- **Attributes** (fields with information about the object like MTBF for a component, number of repair men for a maintenance facility, or allowances for stocks)

- **Behaviors** (methods the object can perform like failing of a component, starting a repair by a repairman, or the fact that a stock is decreased by taking out a component).

Fields within an object can only be changed by a method of this object. Methods can be

- **ASK methods**, where the object is asked by another object to perform a procedure, and where the other object waits until this procedure is finished in order to get certain field values back. However, no simulation time elapses during the waiting period.

- **TELL methods**, where the object is told by another object to invoke a procedure, which is performed independently from the "telling" object. No waiting and no returning of values takes place.

Each TELL-method can

- **Elapse simulation time** during performance

- **Wait** for start of performance until being told or until a fixed point in (simulation) time

- **Send messages** (ASK/TELL) to other objects during and after completion.

Objects can be created dynamically. Fields and methods of objects can be inherited to other objects, or can be kept private. Many objects with the same behavior can be used, distinguished by name only (e.g. in our sample system 306 Subsystems of type A, 306 Subsystems of type B etc.)., but also objects with unique behavior (e.g. the one Direct Exchange Stock at Intermediate Maintenance). Some built-in objects and built-in procedures (used as a built-in method if encapsulated in an object) can be utilized (see [Ref. 21], Appendices D and E). Table 12 on page 51 gives an overview about the objects necessary to model our reduced stochastic model, and indicates the dimensional ranges for each object pertaining to our Sample System.

Table 12. NECESSARY MODSIM OBJECTS

Name(s)	Description	Number necessary for the introduced Sample System	Built-in
CompXXXX	Component-Object, defining the properties of each Subassembly, Assembly and Subsystem.	102 x (12 + 4) = 1632	No
ElemXXXX	Element-Object, defining the properties of each Element	102 x 20 = 2040	No
SystemXXX	System-Object, defining the properties of each unit of the Weapon System	102	No
MaintXX	Maintenance-Object, defining a maintenance facility	17 + 1 = 18	No
QueueXX	Queue-Object, defining a "Waiting for Maintenance"-queue (FIFO) at a maintenance facility	17 + 1 = 18	QueueObj
RepairXX	Repair-Object defining the repair capacity of one repair person at a maintenance facility	17x(1/2/3/4) + (2/3/4/...) = (17/.../68) + (2/...)	No
StockXX	Stock-object, defining stock levels at a maintenance facility	(17 x 12) + 12 = 216	Not with the features required

C. DEVELOPMENT OF MODSIM-II MODULES

MODSIM-II programs can be divided into different "modules", each stored in a separate file. Each module can be compiled separately, saving both time and resources when minor changes have to be made. While the main program (acting like the supervisor of the simulation) is stored in one module called MAIN MODULE, many commonly used variables and types can be stored in one or several DEFINITION MODULEs. Commonly used procedures additionally need to be coded in an accompanying IMPLEMENTATION MODULE. Each Object can also be defined and coded in a separate pair of DEFINITION MODULE and IMPLEMENTATION MODULE. To begin a MODSIM simulation, the best approach is the definition of all variables and types, that are used in several objects, in an initial DEFINITION MODULE "Global", followed by the definition and implementation of all necessary objects with their attributes and the methods they can perform.

1. Global Variables and Types

This is the place to define all fixed parameters listed in Table 3 on page 21. Pertaining to the variable parameters listed in Table 4 on page 22, we can define the parameters R_2, R_{3D} and R_{3C}, which will be controlled by the future user to obtain the respective value for the decision criterion, the Achievable Average System Availability (see also VI.C.), and $DT_{x max}$, which will be known (or simply set to zero) at the begin of the decision process.

In the Type Declaration the known but fixed values for different object fields are set. As an example, the field "Status", defined in Component-Object, is limited to the values "operating", "pausing", "broken" and "standby". Declaring this Type in "Global" ensures that no other value for "Status" can be introduced anywhere else, and avoids the explicit declaration in each object.

The DEFINITION MODULE "Global" is shown in Appendix C.

2. Objects of Weapon System

We will begin the definition of objects with those needed to model the weapon system. The most general module is the Component-Object, having all fields and methods most parts of a technical system have as main characteristics. This Component-Object has the fields

- **Name** - the identifier of the defined component

- **IndentLevel** - indicates the indenture level of the respective component (Subsystem, Assembly, Subassembly or Element)

- **Technology** - indicates main field of electronic technology used in the defined component

- **MasterComponent** - name of component in next higher indenture level the defined component is part of

- **Tenants** - name of components in next lower indenture level which reside inside the object (if any)

- **Status** - indicates if object is operating, pausing, broken or in stand-by

- **BrokenParts** - names of those components at each indenture level that are broken and need to be replaced at the appropriate maintenance facility

- **StandByAvail** - indicates if there is a ready-to-start stand-by-component available

and is able to perform the following methods:

- **ASK METHOD Break** - component is informed about an occurred failure within its tenants, breaks and passes message and names of broken parts on to its master component

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- **ASK METHOD Pause** - each component is informed about an occurred failure within its Weapon System, and pauses in its aging process until its Weapon System is in operating status again

- **TELL METHOD UpAgain** - each component is told to resume operational status again

The Element-Object inherits all fields and methods of Component-Object. It has four additional fields

- **mean** - Mean Time Between Failure

- **alpha** - shape parameter α for Gamma distribution of time between failures

- **TimeToFailure** - period in simulation time until component fails next time

- **Discard** - indicator for irreparable component

and two additional methods.

- **TELL METHOD ComputeNextFail** - the value for field TimeToFailure is computed

- **ASK METHOD Fail** - element is told to fail, and passes message and its own name upwards to its master component

The System-Object inherits all fields of Component-Object, and has four additional fields

- **StartDownTime** - records the point in time at which system failed

- **SumOfDownTimes** - adds (SimulationTime - StartDownTime) to SumOfDownTimes at that point in time at which system returns to operational status

- **AverageAvailability** - keeps track of the average availability value for its weapon system in the simulation

- **MilitaryUnit** - name of military unit to which the system belongs,

has one additional method

- **ASK METHOD DownTime** - system is asked to report SumOfDownTimes

and one method overriding the method with the same name in Component-Object:

- **ASK METHOD Break (OVERRIDE)** - system is informed about an occurred internal failure and orders all of its still operable tenants to pause in the aging process

These three objects are defined and implemented in the module "WeaponSystem". The "DEFINITION MODULE WeaponSystem" and the "IMPLE-MENTATION MODULE WeaponSystem" are both shown in Appendix D.

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3. Objects of Maintenance System

After the definition of the objects needed to model the weapon system, now the objects needed to model the maintenance system are defined. The Organizational-Maintenance-Object has the fields

- **Name** - the identifier of the defined Organizational Maintenance Facility

- **NumberRepairObj** - the number of Repair-Objects within the Maintenance Facility

- **IdleRepairFacilities** - the number of idle Repair-Objects at a point in time

- **IdleFacility** - the idle Repair-Object which will be assigned a job next

- **Stock** - the list of stock levels for all available spare parts

- **JobQueue** - the "waiting for maintenance"-queue

- **ComponentToReplace** - the component which will be assigned next to an idle Repair-Object

- **ResponsibleIntMaintFac** - the name of the next higher Intermediate Maintenance Facility

and is able to perform the following methods:

- **ASK METHOD OrgQueueJob** - adds a failed Subsystem to the "waiting for maintenance"-queue of an Organizational Maintenance Facility

- **ASK METHOD ReportOfIdle** - object is informed about a Repair-Object having become idle

- **TELL METHOD Assign** - assigns a repair job to the asking Repair-Object

- **ASK METHOD SendToRepair** - object is informed that a replaced Subsystem has to be sent to the respective Intermediate Maintenance Facility

The Intermediate-Maintenance-Object inherits all fields and methods of Organizational-Maintenance-Object. It has one additional method

- **ASK METHOD IntQueueJob** - adds a failed Component to the "waiting for maintenance"-queue of an Intermediate Maintenance Facility

and one method overriding the method with the same name in Organizational-Maintenance-Object:

- **TELL METHOD Assign** - assigns a repair job to the asking Repair-Object, too, but applies different administrative and logistic delay times

These two objects are defined and implemented in the module "Maintenance". The "DEFINITION MODULE Maintenance" and the "IMPLEMENTATION MODULE Maintenance" are both shown in Appendix E.

The Repair-Object is defined independently from the Maintenance-Object, and has the following fields:

- **Name** - the identifier of the defined Repair-Object
- **MaintUnit** - the Maintenance-Object the Repair-Object belongs to
- **MaintLevel** - Maintenance Echelon at which jobs are performed at this Repair-Object
- **Qual** - indicates qualification of Repair-Object for certain fields of electronic technology.

Furthermore, Repair-Object has one method:

- **TELL METHOD Fix** - object is told to perform repair

For the Queue-Object, which will line up and release maintenance jobs following the First-In-First-Out (FIFO) policy, the built-in QueueObj can be utilized.

The Stock-Object just has to keep track of the number of a certain component in stock and of the number of eventual reorders that can not be satisfied upon occurrence. It does not have to follow any policy like FIFO or LIFO. It fields are

- **NameOfComp** - name of respective Component-Object
- **NameOfMaintObj** - name of Maintenance-Object where Stock-Object is located
- **Allowance** - maximum number of components in stock
- **Level** - number of components actually in stock at a point in time
- **MaxReOrder** - maximum number of reorders occurring during simulation run,

and its methods are

- **ASK METHOD OffStock** - decreases actual stock level by one
- **ASK METHOD ToStock** - increases actual stock level by one
- **ASK METHOD TrackReOrder** - keeps track of the reorders.

VIII. EVALUATION AND SUMMARY

A. PURPOSE OF THE DECISION AID

As stated in Chapter I, the main purpose of the decision aid to be developed is obtaining reasonable and, as far as achievable at the relevant point of time within the Weapon Acquisition Process, reliable **numbers** for personal and material quantities, which have to be entered into the respective Acquisition Decision Memoranda (ADM).

B. GENERAL SHORTCOME OF THE DECISION AID

Though this decision aid tries to model reality as close as possible, its results are only as good as the quality of the input data - a characteristic known as "garbage in, garbage out". Due to the origin of the MTBF-data for all involved Components, the aid can not offer absolutely reliable results. To avoid poor results and a feeling of dissatisfaction on the user's side, utmost effort has to be concentrated in the building of the data base for MTBF- and MTTR-values (see also VIII.E.1.b.).

C. ACHIEVEMENT BY TIGER

Exploiting the multiple features of an introduced simulation program like TIGER, and intelligently varying the structure of the input data, an **experienced user** can obtain the following **numbers** without any modifications to the code of the program (see Chapter VI):

- *Upper limit for Average System Availability under consideration of technology and general maintenance system*

- *Tactically increased upper limit for Average System Availability*

- *Technology determined absolute upper limit for Average System Availability*

- *Tactically increased technology determined absolute upper limit for Average System Availability*

- *MTBF-values for one unit of the System under each of the conditions stated above*

- *Technology determined MTBF-Values of all Subsystems*

- *Upper limit for Average System Availability at minimum personnel quantity at Organizational Maintenance*

- *Upper limit for Average System Availability for personnel quantity of 2 and more at Organizational Maintenance*

- *Upper limit for Average System Availability at maximum personnel quantity at Organizational Maintenance*

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- *Upper Limit for Spare Parts needed at Organizational Maintenance in the Applied War Scenario*

- *Upper Limit for Spare Parts needed at the Intermediate Maintenance DES in the Applied War Scenario*

- *Upper Limit for the Achievable Average System Availability with Zero Stock Allowance at Organizational Maintenance*

- *Upper Limit for the Achievable Average System Availability with Zero Stock Allowance at all*

- *Technology determined MTBF-Values of all Assemblies*

D. PROBLEMS UNDER TIGER

As shown in Chapter VI, this approach is usable and successful for new Electronic Weapon Systems, as long as the following limitations are applicable:

1. Weapon System will be repaired only in Maintenance Echelon 2 (Organizational Maintenance)

2. The maximum number of Weapon System Units within the responsibility of one Organizational Maintenance Facility does not exceed 31.

These limitations are met by many Weapon Systems to be deployed in the combat support and communication forces. They are definitely exceeded by specific material in the combat support and communication forces, and by most electronic material deployed within the combat forces (see II.C.1.).

The other limitations shown in Table 11 on page 46 (maximum number of Component types = 200, maximum number of distinct Components = 500) generally will not impose any problem, because only the rough design structure of the new system is known at the point in time this decision aid will be applied. If the information available exceeds these limits, the project will have proceeded in the acquisition process, and other tools 12 will be applicable and more appropriate.

E. NECESSARY FUTURE DEVELOPMENTS

To cover all kind of weapon systems the full scale development of the indicated MODSIM-II-program is inevitable. Three major tasks have to be performed.

---

12 like Logistic Support Analysis (LSA) [Ref. 1]

1. **Development of Data Base**

   a. *Weapon System Data*

   These data are no problem, they can be obtained from the existing design papers.

   b. *Component Data*

   The most work intensive task (see VIII.B.) will be the development of the data base for MTBF- and MTTR-data for components defined by their functional characteristics. The evaluation of data for deployed weapon systems can not be performed on a routine basis; it requires experienced personnel with both a background in engineering science, the weapon acquisition process, and in the actual maintenance process at the different military maintenance facilities. As a rough estimate, at least one man-year is necessary to build this data base, and a continuing maintenance is mandatory.

   c. *Deployment Data*

   These data are no problem, they can be obtained from the Mission Need Statement (MNS) or an already existing ADM.

   d. *Maintenance System Data*

   The fixed parameters shown in Table 3 on page 21 are a reasonable, but arbitrary estimate of the real world situation. In case of insufficient other information they can be applied without causing major deviations. A thorough evaluation of existing data might offer more exact data, which might be used to randomize the different delay times in order to introduce even more realism into the model. As a rough estimate, three man-months are necessary to build this part of the data base, and a continuing maintenance is advisable.

   e. *Limitations in Personal and Material Quantities*

   These limitations are not easily obtained, because all personnel involved will try to hide eventually existing realistic values for reasons beyond a pure technical point of view. Like the differentiation of component features based on the manufacturing contractor (see III.B.3.), irrational behavior has to be taken into account, once more pointing to the need for **experienced** users.

2. **Development of a Semi-Automated Decision Aid**

   The procedure shown in Chapter VI in the application of TIGER was a step-by-step off-line process. Each simulation run had to be initiated by the user, though the sequence of input steps was predetermined. Interactions between the user and an on-line

simulation program are only necessary at the following points (Step numbers and Run numbers refer to Chapter VI):

- **After completion of Run 1** to determine the need for the relaxation of tactical requirements and/or the need for an exceptional spare stock of A-Units at the location of the Organizational Maintenance

- **After completion of Run 2** to determine the number of repair personnel at Organizational Maintenance sufficient to achieve the required Average System Availability

- **After completion of a newly designed Run 3**. Run 3 will offer combinations of possible numbers of spare parts in stock at Organizational Maintenance (B-Units) and in stock at Intermediate Maintenance - both in the Direct Exchange Stock (DES, B-Units) and in the general stock (C- and D-Units) - , necessary to offer the Organizational Maintenance "unlimited-like" supply. The user has to determine those combinations that seem to be realistic, and has to start a newly designed Run 4, which finally will offer the number of repair personnel at Intermediate Maintenance, necessary to refill the stock levels, decided upon after Run 3.

So the program to be developed in MODSIM can be structured as a four-step program, asking for a decision by the user after each step. So no decision - while using the decision aid - is made by the program. The program only assists the user with data based on an analysis, so eventually gaining acceptance even from decision makers who might feel uncomfortable with the idea that their intuitive ideas can be performed by a computer.

3. Integration of Specific Features

The scope of subtleties that can be integrated into the final decision aid is nearly infinite. A trade-off between reality and applicability has to be made in order to prevent excessive run times or ridiculous results.

Just a few specialties seem to be reasonable. Though this listing can not be final, the following features (partially also included in the TIGER program) should be included in any further development:

- **Allowable Downtimes** - this feature should be available both on the Subsystem- and the Assembly-level

- **Stand-By** - this feature should be available on all indenture levels

- **Availability of Military Unit** - enlarging the scope of availability data might increase the acceptance also in the military combat community

- **Additional consideration of fractional personnel** - without entering the discussion about the realization of a 0.4-person this feature offers invaluable information about the possibility to combine two "fractional" repair persons for 2 different small systems with comparable technology to one "allround-repair-person" for both systems.

APPENDIX A. SAMPLE INPUT FILE FOR "TIGER"

This appendix contains the second input file for the TIGER Reliability Computer Program (Step 1, Run 2). The reasoning for this input file is described in detail in IV.B.2.

```
    RUN 1/2: NO STOCK OF A-UNITS;  ALLOWABLE DOWNTIMES
250        1.28        1
1 175.     1 15055.


    5    1    0    0    0    0    0    0    0    0    0    0    0    0    0    1
```

11SUBASSEMBLY_A01A	1327.		5.	3
12SUBASSEMBLY_A01B	664.		5.	9
13SUBASSEMBLY_A02A	841.		5.	9
14ELEMENT_A0201	1523.		5.	9
15ASSEMBLY_A03	344.		5.	9
21ELEMENT_B0101	225.		5.	1
23ELEMENT_B0102	534.		5.	9
25ELEMENT_B0201	866.		5.	7
26SUBASSEMBLY_B02A	1167.		5.	5
31ELEMENT_C0101	544.		5.	9
32ELEMENT_C0102	732.		5.	7
33SUBASSEMBLY_C02A	1322.		5.	9
34SUBASSEMBLY_C02B	1003.		5.	4
35SUBASSEMBLY_C03A	210.		5.	9
41SUBASSEMBLY_D01A	375.		5.	5
42SUBASSEMBLY_D01B	445.		5.	9
43SUBASSEMBLY_D01C	1127.		5.	8
44SUBASSEMBLY_D02A	554.		5.	5
45ELEMENT_D0201	1303		5.	3
46ASSEMBLY_D03	628.		5.	2

60

```
11   11
12   12
13   13
14   14
15   15
21   21   22
23   23   24
25   25
26   26
31   31
32   32
33   33
34   34
35   35   36   37
41   41
42   42
43   43
44   44
45   45
46   46
```

UNLIMITED SPARES

```
SYS1    1    4 999
SUBSYSTEM_A   501 0.0
SUBSYSTEM_B   601 0.0
SUBSYSTEM_C   701 0.0
SUBSYSTEM_D   801 35.0
    2 510   11   12
    2 520   13   14
    1 530   15
    3 501 510 520 530
    2 611   21   23
```

```
  2 612   22   24
  1 610  611  612
612 611                                          1
  2 620   25   26
  2 601  610  620
  2 710   31   32
  2 720   33   34
  1 730   35   36   37
 36  35                                          1
 37  35                                          1
 37  36                                          1
  3 701  710  720  730
  3 810   41   42   43
  2 820   44   45
  1 830   46
  3 801  810  820  830
  4 999  501  601  701  801
```

* * * End of Input-File * * *

APPENDIX B. "TIGER"-OUTPUT FOR SAMPLE INPUT FILE

This appendix contains the output for the sample input file shown in Appendix A. The evaluation of this output is described in detail in IV.B.2.

```
*******************************************************************************
*******************************************************************************
**** TIGER SIMULATION FOR RELIABILITY, MAINTAINABILITY, AND AVAILABILITY ****
*******************************************************************************
*******************************************************************************
     RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES


           +++++++++++++++++++ TIGER 8.20 +++++++++++++++++++
           +++++ NAVSEA 05MR  WASHINGTON, DC 20362-5101 +++++
           +++++++++++++++++ (202) 692-2150 +++++++++++++++++


INTIGER


------ (INPUT ECHO) -----------------------------------------------------------


INPUT DATA HIGH VALUES


 DURATION   TYPES   GROUPS   EQUIPS   PH-SEQ   PH-TYP   TRIALS
 15230.00    46      999       46        2        1      250
OUTTIGER                     PAGE
```

RELIABILITY FOR PHASE   1, 1   0.924   RELIABILITY THRU PHASE   1   0.924

AVERAGE AVAILABILITY   AVG. AVAIL. THRU PHASE   1   0.998

          FOR PHASE   1, 1   0.998   TIME (END OF PHASE)   175.000

INSTANT AVAILABILITY   INSTANT AVAILABILITY

          AT BEGINNING OF PHASE 1.000   AT END OF PHASE   0.984

RELIABILITY FOR PHASE   1, 2   0.000   RELIABILITY THRU PHASE   1   0.000

AVERAGE AVAILABILITY   AVG. AVAIL. THRU PHASE   1   0.934

      FOR PHASE   1, 2   0.933   TIME (END OF PHASE)   15230.000

INSTANT AVAILABILITY   INSTANT AVAILABILITY

    AT BEGINNING OF PHASE 0.984   AT END OF PHASE   0.920

FINAL SUMMARY STATS   PAGE

SYSTEM FIGURES OF MERIT AFTER

250 MISSION TRIALS	MEAN	STANDARD DEVIATION OF THE SAMPLE MEAN

AT END OF MISSION:

	MEAN	STD DEV
RELIABILITY	0.000	0.000
RELIABILITY LOWER PRECISION LIMIT (BASED ON STANDARD DEVIATION CRITERIA)	0.000	
INSTANTANEOUS AVAILABILITY	0.920	0.017
AVERAGE AVAILABILITY	0.934	0.000

ESTIMATES OF LONG-TERM VALUES:

	MEAN
MEAN TIME BETWEEN FAILURES	72.3
MEAN TIME TO REPAIR	5.1
AVAILABILITY	0.934

MISSION PERFORMANCE (FAILURE & REPAIR INFORMATION
  CALCULATED FROM TIGER SIMULATION DATA):

	MEAN	STD DEV
MEAN UP TIME	72.3	6.150
MEAN DOWN TIME	5.1	6.150
MEAN REPAIR TIME	5.1	0.004
MEAN ACTIVE REPAIR TIME	0.0	0.000
MEAN TIME TO FIRST FAILURE	299.2	5.744

    TOTAL NO. OF SYSTEM FAILURES =   49152

EQUIP FAILURE SUMMARY BY EQUIPMENT NUMBER

EQUIP. NO.	TYPE NO.	TOTAL EQUIP. FAILURES	AVG. NO. FAILURES PER MISSION	FGC/EIC
11	11	2783	11.132	
12	12	5586	22.344	
13	13	4430	17.720	
14	14	2381	9.524	
15	15	10792	43.168	
21	21	16497	65.988	
22	21	516	2.064	
23	23	6900	27.600	
24	23	85	0.340	
25	25	4291	17.164	
26	26	3122	12.488	
31	31	6870	27.480	
32	32	5065	20.260	
33	33	2742	10.968	
34	34	3707	14.828	
35	35	17652	70.608	
36	35	294	1.176	
37	35	297	1.188	
41	41	9966	39.864	
42	42	8317	33.268	
43	43	3268	13.072	
44	44	6738	26.952	
46	46	5991	23.964	

----------   ----------

TABLE FAILURES TYPE   PAGE

EQUIP FAILURE SUMMARY BY EQUIPMENT TYPE NUMBER

TYPE	TOTAL EQUIP. FAILURES	AVG. NO. FAILURES PER MISSION	MAINTENANCE HOURS	STD. DEV. MAINT. HRS	FGC/EIC
11	2783	11.132	2.752	0.000	
12	5586	22.344	5.544	0.000	
13	4430	17.720	4.448	0.000	
14	2381	9.524	2.358	0.000	
15	10792	43.168	10.816	0.000	
21	17013	68.052	16.845	0.000	
23	6985	27.940	7.002	0.000	
25	4291	17.164	4.305	0.000	
26	3122	12.488	3.159	0.000	
31	6870	27.480	6.930	0.000	
32	5065	20.260	5.057	0.000	
33	2742	10.968	2.802	0.000	
34	3707	14.828	3.762	0.000	
35	18243	72.972	18.168	0.000	
41	9966	39.864	9.877	0.000	
42	8317	33.268	8.241	0.000	
43	3268	13.072	3.344	0.000	
44	6738	26.952	6.801	0.000	
46	5991	23.964	6.148	0.000	
	----------	----------	----------		
	128290	513.158	0.019		

TABLE SPARES LEVEL   PAGE

UNLIMITED SPARES
SUMMARY OF SPARES USED

	ORGANIZATION SPARES			INTERMEDIATE SPARES			DEPOT SPARES		
SPARE TYPE	STOCK	TOTAL USED	USE PER MISSION	STOCK	TOTAL USED	USE PER MISSION	STOCK	TOTAL USED	USE PER MISSION
1	90000	0	0.000	90000	0	0.000	90000	0	0.000
2	90000	0	0.000	90000	0	0.000	90000	0	0.000
3	90000	0	0.000	90000	0	0.000	90000	0	0.000
4	90000	0	0.000	90000	0	0.000	90000	0	0.000
5	90000	0	0.000	90000	0	0.000	90000	0	0.000
6	90000	0	0.000	90000	0	0.000	90000	0	0.000
7	90000	0	0.000	90000	0	0.000	90000	0	0.000
8	90000	0	0.000	90000	0	0.000	90000	0	0.000
9	90000	0	0.000	90000	0	0.000	90000	0	0.000
10	90000	0	0.000	90000	0	0.000	90000	0	0.00Ɔ
11	90000	2783	11.132	90000	0	0.000	90000	0	0.000
12	90000	5586	22.344	90000	0	0.000	90000	0	0.000
13	90000	4430	17.720	90000	0	0.000	90000	0	0.000
14	90000	2381	9.524	90000	0	0.000	90000	0	0.000
15	90000	10792	43.168	90000	0	0.000	90000	0	0.000
16	90000	0	0.000	90000	0	0.000	90000	0	0.000
17	90000	0	0.000	90000	0	0.000	90000	0	0.000
18	90000	0	0.000	90000	0	0.000	90000	0	0.000
19	90000	0	0.000	90000	0	0.000	90000	0	0.000
20	90000	0	0.000	90000	0	0.000	90000	0	0.000
21	90000	17013	68.052	90000	0	0.000	90000	0	0.000
22	90000	0	0.000	90000	0	0.000	90000	0	0.000
23	90000	6985	27.940	90000	0	0.000	90000	0	0.000
24	90000	0	0.000	90000	0	0.000	90000	0	0.000
25	90000	4291	17.164	90000	0	0.000	90000	0	0.000
26	90000	3122	12.488	90000	0	0.000	90000	0	0.000
27	90000	0	0.000	90000	0	0.000	90000	0	0.000
28	90000	0	0.000	90000	0	0.000	90000	0	0.000
29	90000	0	0.000	90000	0	0.000	90000	0	0.000

30	90000	0	0.000	90000	0	0.000	90000	0	0.000
31	90000	6870	27.480	90000	0	0.000	90000	0	0.000
32	90000	5065	20.260	90000	0	0.000	90000	0	0.000
33	90000	2742	10.968	90000	0	0.000	90000	0	0.000
34	90000	3707	14.828	90000	0	0.000	90000	0	0.000
35	90000	18243	72.972	90000	0	0.000	90000	0	0.000
36	90000	0	0.000	90000	0	0.000	90000	0	0.000
37	90000	0	0.000	90000	0	0.000	90000	0	0.000
38	90000	0	0.000	90000	0	0.000	90000	0	0.000
39	90000	0	0.000	90000	0	0.000	90000	0	0.000
40	90000	0	0.000	90000	0	0.000	90000	0	0.000
41	90000	9966	39.864	90000	0	0.000	90000	0	0.000
42	90000	8317	33.268	90000	0	0.000	90000	0	0.000
43	90000	3268	13.072	90000	0	0.000	90000	0	0.000
44	90000	6738	26.952	90000	0	0.000	90000	0	0.000
45	90000	0	0.000	90000	0	0.000	90000	0	0.000
46	90000	5991	23.964	90000	0	0.000	90000	0	0.000

TABLE UNAVA NUM   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT NUMBER FOR FULL SYSTEM

UNAVAILABILITY AND
PERCENT OF UNAVAILABILITY

NAME	NUMBER HRS	UNAVA	PERCENT	EQUIP TYPE	EQUIP NO.	FGC/EIC
ASSEMBLY_A03	52510.1094	0.0138	20.81	15	15	
ELEMENT_C0101	33285.5586	0.0087	13.19	31	31	
SUBASSEMBLY_A01B	27054.7500	0.0071	10.72	12	12	
ELEMENT_C0102	24513.2500	0.0064	9.71	32	32	
SUBASSEMBLY_A02A	21490.1719	0.0056	8.51	13	13	

ELEMENT_B0201	20735.0859	0.0054	8.22	25	25
SUBASSEMBLY_C02B	17946.0820	0.0047	7.11	34	34
SUBASSEMBLY_B02A	15077.8633	0.0040	5.97	26	26
SUBASSEMBLY_A01A	13427.8672	0.0035	5.32	11	11
SUBASSEMBLY_C02A	13275.4180	0.0035	5.26	33	33
ELEMENT_A0201	11482.1250	0.0030	4.55	14	14
ELEMENT_B0101	620.3950	0.0002	0.25	21	22
ELEMENT_B0101	522.2812	0.0001	0.21	21	21
ELEMENT_B0102	209.1828	0.0001	0.08	23	23
ELEMENT_B0102	108.4651	0.0000	0.04	23	24
SUBASSEMBLY_C03A	4.1523	0.0000	0.00	35	35
SUBASSEMBLY_C03A	4.1523	0.0000	0.00	35	36
SUBASSEMBLY_C03A	4.1523	0.0000	0.00	35	37

TABLE UNAVA TYPE   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT TYPE FOR FULL SYSTEM

UNAVAILABILITY AND
PERCENT OF UNAVAILABILITY

NAME	NUMBER HRS	UNAVA	PERCENT	EQUIP TYPE	FGC/EIC
ASSEMBLY_A03	52510.1094	0.0138	20.81	15	
ELEMENT_C0101	33285.5586	0.0087	13.19	31	
SUBASSEMBLY_A01B	27054.7500	0.0071	10.72	12	
ELEMENT_C0102	24513.2500	0.0064	9.71	32	
SUBASSEMBLY_A02A	21490.1719	0.0056	8.51	13	
ELEMENT_B0201	20735.0859	0.0054	8.22	25	
SUBASSEMBLY_C02B	17946.0820	0.0047	7.11	34	
SUBASSEMBLY_B02A	15077.8633	0.0040	5.97	26	
SUBASSEMBLY_A01A	13427.8672	0.0035	5.32	11	

SUBASSEMBLY_C02A	13275.4180	0.0035	5.26	33
ELEMENT_A0201	11482.1250	0.0030	4.55	14
ELEMENT_B0101	1142.6763	0.0003	0.45	21
ELEMENT_B0102	317.6477	0.0001	0.13	23
SUBASSEMBLY_C03A	12.4570	0.0000	0.00	35

TABLE UNREL NUM   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT NUMBER FOR FULL SYSTEM

UNRELIABILITY AND
PERCENT OF MISSION FAILURES

DESCRIPTION	NO. FAILURES	UNREL	PERCENT	EQUIP TYPE	EQUIP NO.	FGC/EIC
ASSEMBLY_A03	171.0	0.6840	68.40	15	15	
ELEMENT_C0101	22.0	0.0880	8.80	31	31	
ELEMENT_C0102	13.0	0.0520	5.20	32	32	
SUBASSEMBLY_C02B	10.0	0.0400	4.00	34	34	
SUBASSEMBLY_A01B	7.0	0.0280	2.80	12	12	
SUBASSEMBLY_A01A	7.0	0.0280	2.80	11	11	
ELEMENT_B0201	6.0	0.0240	2.40	25	25	
ELEMENT_B0101	4.0	0.0160	1.60	21	21	
SUBASSEMBLY_A02A	4.0	0.0160	1.60	13	13	
ELEMENT_B0101	4.0	0.0160	1.60	21	22	
SUBASSEMBLY_B02A	2.0	0.0080	0.80	26	26	

TOTAL NO. MISSION TRIALS = 250
TOTAL NO. MISSION FAILURES FOR FULL SYSTEM = 250
TABLE UNREL TYPE   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT TYPE FOR FULL SYSTEM

UNRELIABILITY AND
PERCENT OF MISSION FAILURES

DESCRIPTION	NO. FAILURES	UNREL	PERCENT	EQUIP TYPE	FGC/EIC
ASSEMBLY_A03	171.0	0.6840	68.40	15	
ELEMENT_C0101	22.0	0.0880	8.80	31	
ELEMENT_C0102	13.0	0.0520	5.20	32	
SUBASSEMBLY_C02B	10.0	0.0400	4.00	34	
ELEMENT_B0101	8.0	0.0320	3.20	21	
SUBASSEMBLY_A01B	7.0	0.0280	2.80	12	
SUBASSEMBLY_A01A	7.0	0.0280	2.80	11	
ELEMENT_B0201	6.0	0.0240	2.40	25	
SUBASSEMBLY_A02A	4.0	0.0160	1.60	13	
SUBASSEMBLY_B02A	2.0	0.0080	0.80	26	

TOTAL NO. MISSION TRIALS = 250
TOTAL NO. MISSION FAILURES FOR FULL SYSTEM = 250
TABLE UNAVA NUM   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT NUMBER FOR SUBSYSTEM_A

UNAVAILABILITY AND
PERCENT OF UNAVAILABILITY

| | | EQUIP | EQUIP | |
NAME	NUMBER HRS	UNAVA	PERCENT	TYPE	NO.	FGC/EIC
ASSEMBLY_A03	53396.4375	0.0140	41.62	15	15	
SUBASSEMBLY_A01B	27526.8477	0.0072	21.46	12	12	
SUBASSEMBLY_A02A	21859.8164	0.0057	17.04	13	13	
SUBASSEMBLY_A01A	13680.1523	0.0036	10.66	11	11	
ELEMENT_A0201	11710.7852	0.0031	9.13	14	14	
TABLE UNAVA TYPE		PAGE				

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT TYPE FOR SUBSYSTEM_A

UNAVAILABILITY AND

PERCENT OF UNAVAILABILITY

| | | | | EQUIP | |
NAME	NUMBER HRS	UNAVA	PERCENT	TYPE	FGC/EIC
ASSEMBLY_A03	53396.4375	0.0140	41.62	15	
SUBASSEMBLY_A01B	27526.8477	0.0072	21.46	12	
SUBASSEMBLY_A02A	21859.8164	0.0057	17.04	13	
SUBASSEMBLY_A01A	13680.1523	0.0036	10.66	11	
ELEMENT_A0201	11710.7852	0.0031	9.13	14	
TABLE UNREL NUM		PAGE			

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT NUMBER FOR SUBSYSTEM_A

UNRELIABILITY AND

PERCENT OF MISSION FAILURES

DESCRIPTION	NO. FAILURES	UNREL	PERCENT	EQUIP TYPE	EQUIP NO.	FGC/EIC
ASSEMBLY_A03	218.0	0.8720	87.20	15	15	
SUBASSEMBLY_A01B	16.0	0.0640	6.40	12	12	
SUBASSEMBLY_A01A	9.0	0.0360	3.60	11	11	
SUBASSEMBLY_A02A	7.0	0.0280	2.80	13	13	

TOTAL NO. MISSION TRIALS = 250

TOTAL NO. MISSION FAILURES FOR SUBSYSTEM_A = 250

TABLE UNREL TYPE   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT TYPE FOR SUBSYSTEM_A

UNRELIABILITY AND
PERCENT OF MISSION FAILURES

DESCRIPTION	NO. FAILURES	UNREL	PERCENT	EQUIP TYPE	FGC/EIC
ASSEMBLY_A03	218.0	0.8720	87.20	15	
SUBASSEMBLY_A01B	16.0	0.0640	6.40	12	
SUBASSEMBLY_A01A	9.0	0.0360	3.60	11	
SUBASSEMBLY_A02A	7.0	0.0280	2.80	13	

TOTAL NO. MISSION TRIALS = 250

TOTAL NO. MISSION FAILURES FOR SUBSYSTEM_A = 250

TABLE UNAVA NUM   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT NUMBER FOR SUBSYSTEM_B

UNAVAILABILITY AND
PERCENT OF UNAVAILABILITY

| | | | | EQUIP | EQUIP | |
NAME	NUMBER HRS	UNAVA	PERCENT	TYPE	NO.	FGC/EIC
ELEMENT_B0201	21394.3789	0.0056	55.52	25	25	
SUBASSEMBLY_B02A	15552.7617	0.0041	40.36	26	26	
ELEMENT_B0101	632.1204	0.0002	1.64	21	22	
ELEMENT_B0101	533.2466	0.0001	1.38	21	21	
ELEMENT_B0102	213.4900	0.0001	0.55	23	23	
ELEMENT_B0102	112.0133	0.0000	0.29	23	24	
TABLE UNAVA TYPE		PAGE				

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT TYPE FOR SUBSYSTEM_B

UNAVAILABILITY AND
PERCENT OF UNAVAILABILITY

| | | | | EQUIP | |
NAME	NUMBER HRS	UNAVA	PERCENT	TYPE	FGC/EIC
ELEMENT_B0201	21394.3789	0.0056	55.52	25	
SUBASSEMBLY_B02A	15552.7617	0.0041	40.36	26	
ELEMENT_B0101	1165.3669	0.0003	3.02	21	
ELEMENT_B0102	325.5032	0.0001	0.84	23	
TABLE UNREL NUM		PAGE			

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT NUMBER FOR SUBSYSTEM_B

UNRELIABILITY AND
PERCENT OF MISSION FAILURES

DESCRIPTION	NO. FAILURES	UNREL	PERCENT	EQUIP TYPE	EQUIP NO.	FGC/EIC
ELEMENT_B0201	164.0	0.6560	65.60	25	25	
SUBASSEMBLY_B02A	67.0	0.2680	26.80	26	26	
ELEMENT_B0101	9.5	0.0380	3.80	21	22	
ELEMENT_B0101	7.0	0.0280	2.80	21	21	
ELEMENT_B0102	2.5	0.0100	1.00	23	23	

TOTAL NO. MISSION TRIALS = 250

TOTAL NO. MISSION FAILURES FOR SUBSYSTEM_B = 250

TABLE UNREL TYPE   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT TYPE FOR SUBSYSTEM_B

UNRELIABILITY AND
PERCENT OF MISSION FAILURES

DESCRIPTION	NO. FAILURES	UNREL	PERCENT	EQUIP TYPE	FGC/EIC
ELEMENT_B0201	164.0	0.6560	65.60	25	
SUBASSEMBLY_B02A	67.0	0.2680	26.80	26	
ELEMENT_B0101	16.5	0.0660	6.60	21	
ELEMENT_B0102	2.5	0.0100	1.00	23	

TOTAL NO. MISSION TRIALS = 250

TOTAL NO. MISSION FAILURES FOR SUBSYSTEM_B = 250

TABLE UNAVA NUM   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT NUMBER FOR SUBSYSTEM_C

UNAVAILABILITY AND

PERCENT OF UNAVAILABILITY

| | | | | EQUIP | EQUIP | |
NAME	NUMBER HRS	UNAVA	PERCENT	TYPE	NO.	FGC/EIC
ELEMENT_C0101	34082.2031	0.0090	37.35	31	31	
ELEMENT_C0102	25083.2070	0.0066	27.49	32	32	
SUBASSEMBLY_C02B	18350.3398	0.0048	20.11	34	34	
SUBASSEMBLY_C02A	13590.7812	0.0036	14.89	33	33	
SUBASSEMBLY_C03A	4.1523	0.0000	0.00	35	35	
SUBASSEMBLY_C03A	4.1523	0.0000	0.0C	35	36	
SUBASSEMBLY_C03A	4.1523	0.0000	0.00	35	37	

TABLE UNAVA TYPE   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT TYPE FOR SUBSYSTEM_C

UNAVAILABILITY AND

PERCENT OF UNAVAILABILITY

| | | | | EQUIP | |
NAME	NUMBER HRS	UNAVA	PERCENT	TYPE	FGC/EIC

ELEMENT_C0101	34082.2031	0.0090	37.35	31
ELEMENT_C0102	25083.2070	0.0066	27.49	32
SUBASSEMBLY_C02B	18350.3398	0.0048	20.11	34
SUBASSEMBLY_C02A	13590.7812	0.0036	14.89	33
SUBASSEMBLY_C03A	12.4570	0.0000	0.01	35

TABLE UNREL NUM   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT NUMBER FOR SUBSYSTEM_C

UNRELIABILITY AND

PERCENT OF MISSION FAILURES

DESCRIPTION	NO. FAILURES	UNREL	PERCENT	EQUIP TYPE	EQUIP NO.	FGC/EIC
ELEMENT_C0101	146.0	0.5840	58.40	31	31	
ELEMENT_C0102	61.0	0.2440	24.40	32	32	
SUBASSEMBLY_C02B	39.0	0.1560	15.60	34	34	
SUBASSEMBLY_C02A	4.0	0.0160	1.60	33	33	

TOTAL NO. MISSION TRIALS = 250

TOTAL NO. MISSION FAILURES FOR SUBSYSTEM_C = 250

TABLE UNREL TYPE   PAGE

RUN 1/2: NO STOCK OF A-UNITS; ALLOWABLE DOWNTIMES

CRITICAL EQUIPMENT BY EQUIPMENT TYPE FOR SUBSYSTEM_C

UNRELIABILITY AND

PERCENT OF MISSION FAILURES

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DESCRIPTION	NO. FAILURES	UNREL	PERCENT	EQUIP TYPE	FGC/FIC
ELEMENT_C0101	146.0	0.5840	58.40	31	
ELEMENT_C0102	61.0	0.2440	24.40	32	
SUBASSEMBLY_C02B	39.0	0.1560	15.60	34	
SUBASSEMBLY_C02A	4.0	0.0160	1.60	33	

TOTAL NO. MISSION TRIALS = 250

TOTAL NO. MISSION FAILURES FOR SUBSYSTEM_C = 250

TABLE REDM   PAGE

RESTRICTED ERLANG DISTRIBUTION MODEL

MTBMF =   299.23

2ND MOMENT ABOUT ORIGIN =   97785.12

SHAPE = 11   M1 =   17.26   M2 =   28.20

T	R-TIGER	R-THEO	DIFF	DIFSQ
175.00	0.924	0.936	-.012	0.000

AFB208I VFNTH : PROGRAM INTERRUPT - FLOATING-POINT UNDERFLOW EXCEPTION

------ (SEE V.B.5.) ---

STANDARD CORRECTIVE ACTION TAKEN. EXECUTION CONTINUING.

| 15230.00 | 0.000 | 0.000 | 0.000 | 0.000 |

AVG ABS DIFF=0.006   MAX ABS DIFF=0.012   SQUARESSUM=0.000

APPENDIX C.   MODSIM-II-CODE FOR MODULE GLOBAL

This appendix contains successfully compiled code for the definition of those vari-
ables and types, that are used in all further definition and implementation modules. The
program part shown is the DEFINITION MODULE "Global", which does not need an
accompanying IMPLEMENTATION MODULE, because no procedure or method has
to be defined.

```
DEFINITION MODULE Global;

FROM GrpMod IMPORT QueueObj;
FROM Debug IMPORT DebugStream;

    VAR

    {Fixed parameters according to Table 3}
    STotal          : INTEGER;
    SUnit           : INTEGER;
    UD              : INTEGER;
    DC              : INTEGER;
    UC              : INTEGER;
    MartA           : REAL;
    MartB           : REAL;
    LDTstock        : REAL;
    LDTDES          : REAL;
    LDTsupply       : REAL;
    ADT2            : REAL;
    ADT3            : REAL;
```

{Variable parameters according to Table 4; stock levels handled by
StockObject}
```
R2              :  INTEGER;
R3D             :  INTEGER;
R3C             :  INTEGER;
```

{Variable requirement parameter according to Table 5 handled by
ComponentObject}

TYPE

```
IndentLevelType  = (System, Aunit, Bunit, Cunit, Dunit);
StatusType       = (operating, pausing, broken, standby);
MaintLevelType   = (Organizational, Intermediate);
QualType         = (Electronic, Optronic, Communication,
                    WeaponGuidance, RADAR, LASER, Electrical,
                    Mechanical);
```

```
ComponentTypeQueue   = QueueObj;
BrokenPartsTypeQueue = QueueObj;
IdleRepairTypeQueue  = QueueObj;
WaitingJobTypeQueue  = QueueObj;
StockTypeQueue       = QueueObj;
```

END MODULE.

APPENDIX D. MODSIM-II-CODE FOR MODULE WEAPONSYSTEM

This appendix contains successfully compiled code for the three objects necessary to model the behavior of a four-indenture-level electronic weapon system:

1. Component-Object
2. Element-Object
3. WeaponSystem-Object

The first program part shown is the DEFINITION MODULE, followed by the accompanying IMPLEMENTATION MODULE.

```
DEFINITION MODULE WeaponSystem;

FROM SimMod IMPORT SimTime;
FROM RandMod IMPORT RandomObj;
FROM GrpMod IMPORT QueueObj;
FROM Maintenance IMPORT OrgMaintObj;
FROM Global IMPORT ALL StatusType, ComponentTypeQueue,
                  ALL IndentLevelType,ALL QualType,
                  BrokenPartsTypeQueue;

  EXPORTTYPE
     CompObj = OBJECT; FORWARD;
     WeaponSystemObj = OBJECT; FORWARD;


  TYPE
     CompObj = OBJECT

           Name            : STRING;
           IndentLevel     : IndentLevelType;
           Technology      : QualType;
           MasterComponent : CompObj;
```

```
Tenants         : ComponentTypeQueue;
Status          : StatusType;
BrokenParts     : BrokenPartsTypeQueue;
StandByAvail    : BOOLEAN;


ASK METHOD Break (IN BrokenParts : BrokenPartsTypeQueue);
    {CompObj is informed about an occurred failure within its
     ComponentTypeQueue, and passes message and the names of the
     broken components at each respective IndentLevel upwards to
     its MasterComponent}


ASK METHOD Pause;
    {CompObj is informed about an occurred failure within its
     WeaponSystemObj, and is told to pause in its aging process
     until WeaponSystemObj is up again}


ASK METHOD UpAgain;
    {CompObj is told to change to Status=operational}


END OBJECT;


ElementObj = OBJECT(CompObj)


mean            : REAL;
alpha           : REAL;
    {Gamma distribution for time between failures}
TimeToFailure   : REAL;
Discard         : BOOLEAN;


TELL METHOD ComputeNextFail;
    {ElementObj is told to calculate its next time to failure}
```

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```
    ASK METHOD Fail;
        {ElementObj is asked to fail, and passes message and its own
         name upwards to its MasterComponent}


END OBJECT;


WeaponSystemObj = OBJECT(CompObj)


    StartDownTime        : REAL;
    SumOfDownTimes       : REAL;
    AverageAvailability  : REAL;
    MilitaryUnit         : OrgMaintObj;


    ASK METHOD DownTime (OUT AverageAvailability : REAL);
        {WeaponSystemObj is asked to report SumOfDownTime}


    OVERRIDE
    ASK METHOD Break (IN BrokenParts : BrokenPartsTypeQueue);
        {WeaponSystemObj is informed about an occurred failure within
         its ComponentTypeQueue, and orders its entire
         ComponentTypeQueue to pause}


    END OBJECT;


END MODULE.




IMPLEMENTATION MODULE WeaponSystem;


FROM SimMod IMPORT SimTime;
FROM RandMod IMPORT RandomObj;
FROM GrpMod IMPORT QueueObj;
```

```
FROM Maintenance IMPORT OrgMaintObj, IntMaintObj;
FROM Global IMPORT ALL IndentLevelType, ALL StatusType, ALL QualType,
                ComponentTypeQueue,BrokenPartsTypeQueue;


VAR
    RandomGenerator : RandomObj;
    i               : INTEGER;


OBJECT CompObj;

    ASK METHOD Break (IN BrokenParts : BrokenPartsTypeQueue);

        BEGIN
            Status := broken;
            ASK BrokenParts TO Add (SELF);
            IF IndentLevel <> System
                ASK MasterComponent TO Break (BrokenParts);
            END IF;
        END METHOD;


    ASK METHOD Pause;
        BEGIN
            Status := pausing;
            Tenants := ASK Tenants First();
            FOR i:=1 TO ASK Tenants numberIn
                Status := pausing;
                Tenants := ASK Tenants Next (SELF);
            END FOR;
        END METHOD;


    ASK METHOD UpAgain;

        BEGIN
            Status := operating;
```

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```
    END METHOD;

END OBJECT;

OBJECT ElementObj;

    TELL METHOD ComputeNextFail;

        BEGIN
            TimeToFailure := ASK RandomGenerator Gamma (mean,alpha);
            WAIT DURATION TimeToFailure
            END WAIT;
            ASK SELF TO Fail;
        END METHOD;

    ASK METHOD Fail;

        BEGIN
            Status := broken;
            ASK BrokenParts TO Add (SELF);
            ASK MasterComponent TO Break (BrokenParts);
        END METHOD;

END OBJECT;

OBJECT WeaponSystemObj;

    ASK METHOD Break (IN BrokenParts : BrokenPartsTypeQueue);

        BEGIN
            Status := broken;
            StartDownTime := SimTime();
            Tenants := ASK Tenants First();
            FOR i:=1 TO ASK Tenants numberIn
```

```
                Status := pausing;
                Tenants := ASK Tenants Next (SELF);
            END FOR;
            ASK MilitaryUnit TO OrgQueueJob (SELF);
        END METHOD;


    ASK METHOD DownTime (OUT AverageAvailability : REAL);


        BEGIN
            AverageAvailability := (SimTime() - SumOfDownTimes)/ SimTime();
        END METHOD;


    END OBJECT;


END MODULE.
```

APPENDIX E.   MODSIM-II-CODE FOR MODULE MAINTENANCE

This appendix contains successfully compiled code for the two objects necessary to model the behavior of the two studied major Maintenance-Echelon-Levels in the Three-Level-Maintenance-System of the German Army:

1. Organizational-Maintenance-Object
2. Intermediate-Maintenance-Object

The first program part shown is the DEFINITION MODULE, followed by the accompanying IMPLEMENTATION MODULE.

```
DEFINITION MODULE Maintenance;


FROM WeaponSystem IMPORT CompObj, WeaponSystemObj;
FROM GrpMod IMPORT QueueObj;
FROM Global IMPORT ADT2,ADT3,LDTstock,LDTDES,LDTsupply,
                   ALL IndentLevelType,BrokenPartsTypeQueue,
                   IdleRepairTypeQueue, WaitingJobTypeQueue,
                   StockTypeQueue;
FROM Repair IMPORT RepairObj;


EXPORTTYPE
   OrgMaintObj = OBJECT; FORWARD;
   IntMaintObj = OBJECT; FORWARD;


TYPE
   OrgMaintObj = OBJECT


      Name                 : STRING;
      NumberRepairObj      : INTEGER;
      IdleRepairFacilities : IdleRepairTypeQueue;
      IdleFacility         : RepairObj;
```

```
    Stock                : StockTypeQueue;

    JobQueue             : WaitingJobTypeQueue;

    ComponentToReplace   : CompObj;

    ResponsibleIntMaintFac: IntMaintObj;

    j                    : INTEGER;

    r                    : INTEGER;


    ASK METHOD OrgQueueJob (IN WeaponSystem : WeaponSystemObj);
        {OrgMaintObj is told to receive a WeaponSystemObj and to queue
         its broken Subsystem into its JobQueue}


    ASK METHOD ReportOfIdle (IN RepairFacility : RepairObj);
        {MaintObj is told to receive a RepairObj and either to assign
         it a job or to queue it into its IdleRepairQueue}


    TELL METHOD Assign (IN RepairFacility : RepairObj;
                        IN ComponentToReplace : CompObj);
        {MaintObj is asked to assign a CompObj to the asking RepairObj;
         both the admistrative delay time ADT2 and the respective
         logistic delay time LDTstock / LDTDES / LDTsupply are
         considered within this method}


    ASK METHOD SendToRepair (IN Component : CompObj);
        {MaintObj is asked by the telling RepairObj that a replaced
         Com pObj has to be sent to the ResponsibleIntMaintFac}


END OBJECT;


IntMaintObj =  OBJECT(OrgMaintObj)


    ASK METHOD IntQueueJob (IN Component : CompObj);
        {IntMaintObj is told to receive a CompObj and to queue it into its
         JobQueue; if queued CompObj is first in JobQueue, initiate its
         assignment to the first RepairObj of IdleRepairObjQueue}
```

```
    OVERRIDE
    TELL METHOD Assign (IN RepairFacility : RepairObj;
                        IN ComponentToReplace : CompObj);
       {MaintObj is asked to assign a CompObj to the asking RepairObj;
        both the admistrative delay time ADT3 and the respective logistic
        delay time LDTstock / LDTsupply are considered within this method}


    END OBJECT;


END MODULE.




IMPLEMENTATION MODULE Maintenance;


FROM WeaponSystem IMPORT CompObj, WeaponSystemObj;
FROM GrpMod IMPORT QueueObj;
FROM Global IMPORT ADT2,ADT3,LDTstock,LDTDES,LDTsupply,
                   ALL IndentLevelType,BrokenPartsTypeQueue,
                   IdleRepairTypeQueue, WaitingJobTypeQueue,
                   StockTypeQueue;
FROM Repair IMPORT RepairObj;


OBJECT OrgMaintObj;

    ASK METHOD OrgQueueJob (IN WeaponSystem : WeaponSystemObj);
       BEGIN
          ComponentToReplace := ASK WeaponSystem.BrokenParts Last();
          r := ASK IdleRepairFacilities numberIn;
          IF r=0
             ASK JobQueue TO Add (ComponentToReplace);
          ELSE
```

```
                IdleFacility := ASK IdleRepairFacilitiesRemove();
                TELL SELF TO Assign (IdleFacility, ComponentToReplace);
            END IF;
        END METHOD;


    ASK METHOD ReportOfIdle (IN RepairFacility : RepairObj);
        BEGIN
            j := ASK JobQueue numberIn;
            IF j=0
                ASK IdleRepairFacilities Add (RepairFacility);
            ELSE
                ComponentToReplace := ASK JobQueue Remove();
                TELL SELF TO Assign (RepairFacility, ComponentToReplace);
            END IF;
        END METHOD;


    TELL METHOD Assign   (IN RepairFacility : RepairObj;
                          IN ComponentToReplace : CompObj);


        BEGIN
            TELL RepairFacility TO Fix (ComponentToReplace);
        END METHOD;


    ASK METHOD SendToRepair (IN Component : CompObj);


        BEGIN
            ASK ResponsibleIntMaintFac TO IntQueueJob (Component);
        END METHOD;


    END OBJECT;


OBJECT IntMaintObj;


    ASK METHOD IntQueueJob (IN Component : CompObj);
```

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```
BEGIN
    ComponentToReplace := ASK Component.BrokenParts Last();
    r := ASK IdleRepairFacilities numberIn;
    IF r=0
        ASK JobQueue TO Add (ComponentToReplace);
    ELSE
        IdleFacility := ASK IdleRepairFacilities Remove();
        TELL SELF TO Assign (IdleFacility, ComponentToReplace);
    END IF;
END METHOD;


TELL METHOD Assign  (IN RepairFacility : RepairObj;
                     IN ComponentToReplace : CompObj);


    BEGIN
        TELL RepairFacility TO Fix (ComponentToReplace);
    END METHOD;


END OBJECT;


END MODULE.
```

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